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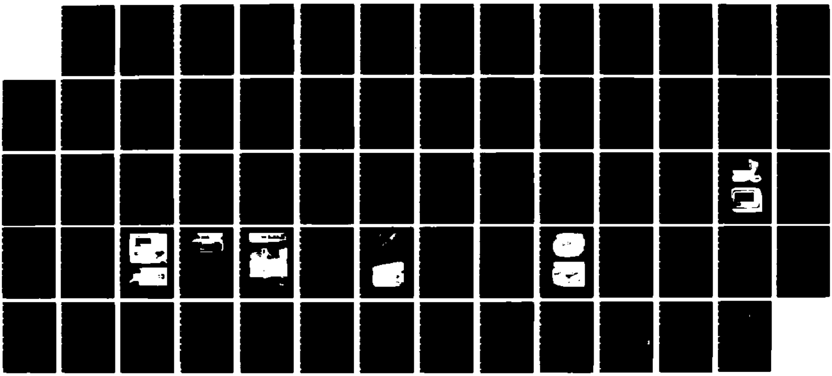

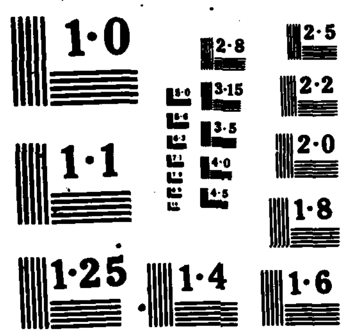

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NCEL
Technical Note

February 1986
By A.P. Smith
Sponsored By Naval Facilities
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AD-A168 270

UNDERWATER NONDESTRUCTIVE TESTING OF CONCRETE: AN EVALUATION OF TECHNIQUES

ABSTRACT Three commercially available instruments for testing concrete above water were successfully modified for underwater use and evaluated in laboratory and field tests. One instrument was a magnetic rebar locator that locates rebar in concrete structures and measures the amount of concrete cover over the rebar. Another instrument was a Schmidt hammer that evaluates the surface hardness of the concrete and obtains a general/condition assessment. The third instrument was ultrasonic test equipment that estimates compressive strength, detects cracks, and provides a general condition rating of the concrete based on sound velocity measurements.

~~Laboratory and field tests did not reveal any problems with~~ the fundamental operation of each instrument after they were modified. There was a 23% shift in the output data for the Schmidt hammer as a result of the modifications, but this shift can be eliminated by designing it for underwater use. The modifications did not affect the data from the other two instruments, and all of the instruments were easily operated by a diver.

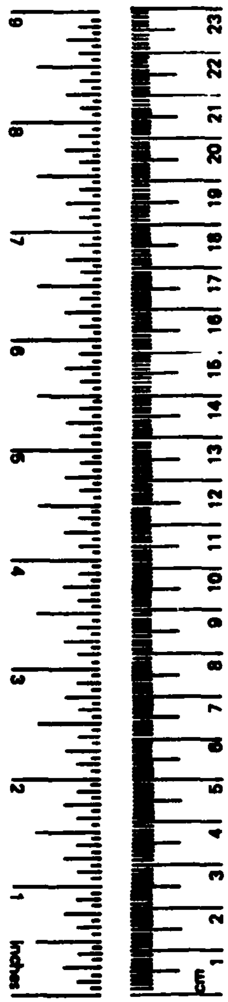
NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

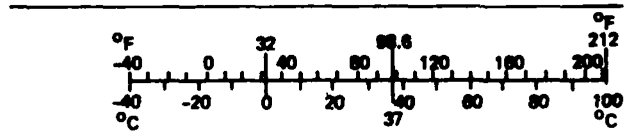
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Three commercially available instruments for testing concrete above water were successfully modified for underwater use and evaluated in laboratory and field tests. One of the three instruments was a magnetic rebar locator that locates rebar in concrete structures and measures the amount of concrete cover over the rebar. Another instrument was a Schmidt hammer that evaluates the surface hardness of the concrete and obtains a general

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condition assessment. The third instrument evaluated was ultrasonic test equipment that estimates compressive strength, detects cracks, and provides a general condition rating of the concrete based on sound velocity measurements.

Laboratory and field tests did not reveal any problems with the fundamental operation of each instrument after they were modified. There was a 23% shift in the output data for the Schmidt hammer as a result of the modifications, but this shift can be eliminated by designing it for underwater use. The modifications did not affect the data from the other two instruments, and all of the instruments were easily operated by a diver.

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EXECUTIVE SUMMARY

Three commercially available instruments for testing concrete above water were successfully modified for underwater use and evaluated in laboratory and field tests. Each instrument represents a different technique for evaluating concrete structures. Instruments for the following methods were tested:

a. A magnetic rebar locator that can be used to locate rebar in concrete structures and measure the amount of concrete cover over the rebar.

b. A Schmidt hammer that can be used to evaluate the surface hardness of the concrete and obtain a general condition assessment.

c. Ultrasonic test equipment that can be used to estimate compressive strength, detect cracks, and provide a general condition rating of the concrete, based on sound velocity measurements.

Laboratory and field tests did not reveal any problems with the fundamental operation of each instrument. Only the Schmidt hammer showed a shift in output data (23%) as a result of the modifications. This shift can be eliminated by modifying the design. Modification for underwater operation did not affect data from the other two instruments, and all instruments were easily operated by a diver.

A prototype concrete inspection system consisting of an R-Meter, Schmidt hammer, ultrasonic test equipment, and a common data acquisition system is recommended for development.

CONTENTS

INTRODUCTION

Concrete is the most common construction material used by the Navy in waterfront structures. It is estimated that more than 40% of Navy piers consist of a concrete deck supported by concrete piles (Ref 1). In addition, concrete is also used extensively for retaining walls, encasement of other materials such as steel piles, and pavement. To adequately maintain these structures, periodic inspections are required, both above and below water.

Currently, underwater inspections of concrete structures are conducted visually to assess the condition of the facility. The qualitative data obtained from these inspections are generally inadequate to accurately assess the condition of the structure. New techniques and equipment are required to provide more quantitative data from underwater inspections of concrete structures.

The Naval Civil Engineering Laboratory (NCEL), under the sponsorship of the Naval Facilities Engineering Command (NAVFAC), has initiated a project to assess potential techniques for nondestructive testing (NDT) of concrete underwater. This report presents the results of laboratory and field evaluations of the Schmidt hammer, magnetic rebar locator, and ultrasonic testing equipment, all of which were modified for underwater use.

BACKGROUND

Many techniques for testing concrete above water have been developed and generally are well documented in the literature. Most of these techniques are discussed in Reference 2, published by the American Concrete Institute, which provides a good summary of nondestructive methods of testing concrete on land. Those techniques most easily adapted for inspecting concrete structures underwater have been identified and are listed below (Ref 3).

- Magnetic Rebar Location - Magnetic rebar location devices detect the distortion in a magnetic flux field caused by the pressence of metallic rebar.

- Rebound Method - The compressive strength of the concrete is correlated with the rebound height of a spring driven mass after impact.

- Ultrasonic Testing - The transit time of high frequency sound waves is used to assess the condition of the concrete and detect internal defects.

- Radiographic Tomography - The absorption and scatter of radiation is used to produce a visual image of the concrete cross section at the point of inspection, indicating the thickness and density.

- Surface Hardness - The compressive strength of the concrete is correlated with the size of an indentation produced by a mass impacting the surface.

- Penetration Techniques - The compressive strength of concrete is correlated with the depth of penetration of a hardened probe that is explosively fired into the concrete surface.

- Pullout Testing Techniques - The compressive strength of concrete is correlated with the force required to pullout an anchor rod embedded in the surface of the concrete. (This is a destructive test and not desirable for underwater inspections because of the probability of exposing rebar.)

- Coring - This is the standard technique for determining the quality and strength of concrete. Underwater coring equipment has been developed and is available. Generally, coring should only be considered when other inspection techniques indicate that a serious problem exists.

The first four of these techniques were identified as offering the greatest potential to improve the Navy's ability to inspect concrete structures underwater (Ref 4). This report presents the results of laboratory and field evaluations of selected equipment that use the first three techniques:

Technique	Commercial Name
Magnetic Rebar Location	R-Meter
Rebound Method	Schmidt Hammer
Ultrasonic Testing	V-Meter

The fourth technique, radiographic tomography, is not included in the report. However, a feasibility analysis and conceptual design of a tomography system to inspect concrete and timber have been completed and are described in References 5, 6, and 7.

CONCRETE DETERIORATION AND INSPECTION REQUIREMENTS

The most common damage resulting in the premature deterioration of concrete structures in or near seawater is cracking and loss of material or cross section. Softening of the concrete due to chemical action is another form of damage less common than cracking. The damage to concrete is generally most severe in the splash and tidal zones.

Damage from corrosion of the steel reinforcement occurs when the corrosion products cause the volume of the structural element to expand, resulting in tensile stresses and cracking. As corrosion progresses, the corrosion products continue to expand, causing more cracking.

Eventually, spalling occurs, exposing the steel reinforcement. Rust stains on the concrete surface are usually the first visual indication of corrosion of the reinforcement. Once these visual signs are evident, however, corrosion is well advanced, requiring costly repairs or replacement of the structure.

Damage from overloading may occur due to ship impact or may be generated by excessive pile driving forces during construction. The initial damage may be only hairline cracks that go unnoticed. Subsequent intermittent wetting may initiate corrosion of the reinforcement, causing the cracks to increase in number and size, leading eventually to spalling. Also, damage to concrete elements caused by freezing and thawing involves penetration of the water into small cracks which are then expanded and propagated by the forces generated when the water freezes. The common causes of damage to concrete are summarized below:

Chemical	Mechanical
Corrosion of Reinforcement	Accidental Overload
Sulfate Attack	Abrasion
Chemical Reaction of Aggregates	Freeze-Thaw

Inspection data and accuracy requirements were established for the underwater inspection of concrete structures (Ref 1). Equipment and inspection techniques are required that can detect the presence and location of cracks greater than 1/32-inch wide, diameter of rebar to within 4% of the original diameter, concrete strength to within 12% of the mean strength of the entire element, and location of rebar and depth of concrete cover to within 1/4 inch. These data and accuracy requirements were derived from structural analysis criteria.

Three types of inspection are distinguishable by the resources and preparation needed to do the work and the type of damage or defect that is detectable (Ref 1). Therefore, the type of damage detected depends upon the level of inspection described below.

- Level I - General Visual Inspection. This type of inspection does not involve cleaning any structural elements and can be conducted more rapidly than the other types of inspection.

- Level II - Close-Up Visual Inspection. This type of inspection generally involves cleaning of structural elements and normally is restricted to the critical areas of the structural element.

- Level III - Nondestructive Testing. This type of inspection is conducted to detect hidden or incipient damage. Generally, the equipment and test procedures will be more sophisticated than either the Level I or Level II inspection.

The evaluation test results presented in this report are for equipment that would be used to perform a Level III inspection on underwater concrete structures. Table 1 summarizes the purpose of each inspection and the type of damage that each level of inspection will detect.

MAGNETIC REBAR LOCATION - R-METER

General Description and Operation

Reinforcing bar location devices detect the disturbance in a magnetic flux field caused by the presence of magnetic material. The magnitude of this disturbance is used to determine the location and orientation of steel reinforcing bars in concrete and to measure the depth of concrete cover over the rebar. These instruments are commercially available for measuring the depth of concrete cover in dry environments.

Rebar locator devices typically consist of a U-shaped magnetic core upon which two coils are mounted. A magnetic field is produced by applying an alternating current to one coil and measuring the current induced in the other coil. The magnitude of the induced current is affected by both the diameter of the rebar and its distance from the coils. Therefore, if either of these parameters is known, the other can be determined. By scanning with the probe until a peak reading is obtained, the location of the rebar can also be determined. A maximum deflection of the meter needle will occur when the axes of the probe poles are parallel to and directly over the axis of a reinforcing bar, thus indicating orientation.

An R-meter rebar locator (Model C-4956) was purchased and modified for underwater use and is shown in Figure 1. This instrument is powered by a rechargeable 12-volt, 4.5-amp-hour storage battery and will operate for about 10 hours between charges. To fully recharge the battery from a completely discharged state requires about 16 hours. A detailed operations manual is supplied with the unit (Ref 8).

The R-Meter is calibrated for rebar that varies from No. 3 to No. 16 in size. (Appendix A defines the nominal dimensions of reinforcing steel.) The R-Meter can be used to measure the depth of concrete cover over rebar in the range of 1/4 to 8 inches, or conversely, it can measure the diameter of the rebar. The actual value of concrete cover measured corresponds to the distance between the tips of the probe and the top of the reinforcing bar as illustrated in Figure 2. The best accuracy (±10%) is obtained for concrete cover less than 4 inches thick.

To obtain maximum accuracy for concrete cover measurements when using the R-Meter, the meter zero must be set accurately and rechecked frequently. The meter zero will drift with the battery charge level and temperature variations. Figure 3 shows the effect of zero setting error on the measurement of concrete cover (Ref 8). Curve A represents the condition of thick concrete cover and smaller diameter rebar. For this situation, small zero offsets introduce significant errors in the measurement. Curve D represents the condition of very thin concrete cover and larger diameter rebar. For this situation, zero offset does not introduce any significant error in the measurement. Curves B and C represent other measurement conditions and indicate that this effect is more pronounced for increased concrete cover and smaller diameter rebar.

The primary limitation that effects the operation of the R-Meter is the presence of other metallic objects in the vicinity of the rebar where the measurement is being made. For example, in heavily reinforced structures, the effect of nearby rebar cannot be eliminated and accurate depth readings are difficult or impossible. The effects of parallel 1-inch diameter rebar, located 2 inches below the surface of the concrete, is

shown in Figure 4 (Ref 8). Theoretically, if the separation of the axes of two parallel rebars is at least three times the thickness of the concrete cover, this effect can be neglected. In routine measurements, if the meter needle drops to a value of one or less on the linear scale when the probe is between the two bars, the effect can be neglected.

The presence of rebar perpendicular to the axis of the probe has much less effect on the measurement of concrete cover than that of parallel rebar and in most instances it can be ignored. For example, if the probe is not positioned directly above the perpendicular rebar or the perpendicular rebar is located beneath the rebar under test, the effect is negligible. The operations manual provides guidance to reduce these limitations and improve the measurement accuracy.

Modifications for Underwater Use

The first attempt at modifying the R-Meter for underwater use consisted of placing the entire instrument in a waterproof housing, 12 inches in diameter and 6 inches deep. The probe was located directly below the readout inside the waterproof housing. The readout was visible through a clear acrylic top. In order to operate the modified R-Meter underwater, it was necessary for the diver to use both hands to position the instrument. Once the R-Meter was positioned the diver had to manually log the data. This sequence of events was difficult to accomplish and inefficient. Consequently, this approach was dropped in favor of waterproofing only the test probe. The electronics were kept topside, where the data were automatically recorded.

To evaluate the R-Meter underwater using the second approach, it was necessary to waterproof the test probe, provide a remote indicator to orient the diver while using the instrument, and increase the length of the interconnecting cable between the test probe and the readout that was kept topside. The modified R-Meter is shown in Figure 5, including a closeup of the test probe.

To waterproof the test probe a thin layer of epoxy was deposited over the exposed metal tips. The remote indicator was a small voltmeter that duplicated the meter movement from the deck unit. The voltmeter was mounted in a PVC housing and attached to the test probe. The diver used this indicator to locate rebar and orient the probe when measuring the depth of concrete cover. The actual measurement of concrete cover was made topside; the diver did not log any readings. The housing also contained a pressure gauge to measure the water depth and a waterproof connector. An underwater electrical cable (180 feet long) connected the probe to the deck unit.

Laboratory Test Results

The modified R-Meter was tested in the laboratory to determine if the modifications had any effect on the output and to check its performance underwater. To evaluate the performance of the modified R-Meter, measurements were taken on four concrete test specimens, each containing a different size of rebar. The size of each test block was 6x6x18 inches and the rebar was located slightly off-center. Measurements were taken before the modifications were done, after they were completed, and with

the modified probe submerged in water. Figure 6 shows the R-Meter and one of the test blocks. Table 2 presents the test data in terms of measured concrete cover before the modifications were made and after modification with the probe submerged in water. Figure 7 is a plot of data from the same tests with readings from the linearized scale used for comparison.

The test results showed no significant change in output data after the probe was modified to operate underwater. The maximum deviation was +1/8 inch and indicated increased concrete cover. Since the epoxy coating deposited over the probe tips did raise the probe above the surface of the concrete about 0.05 inches, it was expected that the instrument should indicate increased concrete cover. However, interpretation of the readout to better than 1/16 of an inch is not practical, especially for thicker coverage (>4 inches) where 1/8 of an inch is probably more realistic.

A qualitative test was performed in the seawater test tank at NCEL to evaluate the performance of divers using the R-Meter. A concrete slab (4x4x0.67 feet) containing different lengths of No. 5 rebar was used as a test specimen. NCEL divers surveyed both sides of the slab with the R-Meter probe and marked the location of the rebar.

The results of the evaluation showed that the modified R-Meter was very easy for the diver to use. Rebar with less than 4 inches of concrete cover was easily detected and accurately located. Rebar with concrete cover between 4 and 6 inches was more difficult to locate and rebar with concrete cover greater than 6 inches was very difficult to locate because of the small deflection on the remote readout. Also, parallel rebars were not distinguishable from one another when the concrete cover was 4 inches and the rebar spacing was 6 inches. Measurements from the opposite side of the slab did detect the parallel rebars where the concrete cover was only 2 inches.

In summary, the R-Meter can be used successfully underwater to inspect concrete structures and perform the following functions, within the basic limitations of the instrument:

1. Determine the location of rebar in concrete structures, both orientation (±10 degrees) and position (±1/2 inch).

2. Measure the depth of concrete cover over rebar for the range of 1/4 to 8 inches thick with an accuracy of about ±10%.

3. Determine the size of standard rebar (No. 3 to No. 16) with an accuracy of ±10% which is roughly equivalent to one standard rebar size.

The operation of the modified R-Meter in the laboratory did not reveal any problems with the fundamental operation of the instrument and there was no effect on the output data after the modification.

SCHMIDT HAMMER

General Description and Operation

The Schmidt hammer utilizes the rebound method for determining the compressive strength of concrete. This is accomplished by correlating the rebound height of a spring-driven mass after it impacts the surface of the concrete with the compressive strength of the concrete under test. A Schmidt hammer, Model RM 710, Type L, modified for underwater use, is shown in Figure 8. A cutaway view of the hammer, illustrating the internal mechanisms, is shown in Figure 9.

The Schmidt hammer is principally a surface hardness tester. It consists of a spring-driven mass that slides on a guide bar within the tubular housing as shown in Figure 9. To carry out a test, the impact plunger is pressed strongly against the concrete surface under test. This releases the spring-loaded mass from its locked position causing an impact. The mass then rebounds, taking the rider with it along the guide scale. By pushing a button, the operator can hold the rider in position while the index is read to the nearest whole number. This value is referred to as the rebound number and can vary over the range of 10 - 100 with higher numbers indicating stronger concrete. It is recommended that a minimum of 12 readings be taken per test site and averaged after discarding the minimum and maximum values (Ref 9). A general calibration chart (provided by Soiltest, Inc., Evanston, Illinois) that relates the rebound number to cylinder compressive strength for the Model RM 710 Schmidt hammer is shown in Figure 10.

The Schmidt hammer has numerous limitations that should be recognized when using this instrument to obtain surface hardness data. For example, the test results obtained with the hammer are effected by the following:

1. The surface of the concrete under test has an important effect on the accuracy of the test results. Higher rebound numbers were obtained from smoother surfaces and the scatter in the data was less. Minimizing the data scatter increases the confidence in the test results. Thus, underwater concrete surfaces must be thoroughly cleaned and smoothed with something like a carborundum stone before measurements are taken.

2. Surface and internal moisture conditions of the concrete will also affect the results. Saturated concrete tends to show rebound readings five points lower than when tested dry. This will affect the comparison of data taken above and below the waterline.

3. The type of coarse aggregate and cement significantly effects the correlation of the rebound numbers with actual compressive strength of the concrete under test. A calibration curve is required for each particular concrete mix to assure accuracy. This is not practical for most situations.

4. Size, shape, rigidity, and age of the concrete become important when testing small concrete samples or recently poured concrete. This should not be a concern for the underwater inspection application.

Because of these limitations, which are discussed more fully in Reference 2, the estimation of concrete compressive strength obtained with a rebound hammer is accurate only to about ±25%. This applies to concrete specimens cast, cured, and tested under identical conditions as those from which the calibration curves were established. Because of the lack of accurate calibration data correlating compressive strength with rebound numbers, the Schmidt hammer is primarily useful for checking surface hardness and uniformity of concrete. It can also be used to compare one concrete against another if they are assumed to be reasonably similar.

Modifications for Underwater Use

To use the Schmidt hammer underwater, it was necessary to place the hammer in a waterproof housing with an O-ring seal on the impact plunger shaft. This required extending the impact plunger approximately 4 inches. In order to eliminate the diver recording data manually, an electrical pickup was added to sense the position of the rebound rider. This allowed the diver to take measurements as rapidly as possible. A 150-foot-long cable was used to connect the electrical pickup to the data acquisition system on the surface. Figure 11 shows the Schmidt hammer modified for underwater use.

Laboratory Test Results

Laboratory tests were performed on the Schmidt hammer to evaluate its basic performance. The modified Schmidt hammer was tested to determine if the modifications had any effect on the output and to evaluate its basic performance underwater. Test results obtained with the modified hammer were compared against the test data obtained with a standard Schmidt hammer.

The basic Schmidt hammer calibration was checked using a test anvil provided by the manufacturer. The anvil is made of hardened steel and forms a surface upon which a reference reading can be obtained to check the calibration of the rebound hammer. Internal adjustments can be made in the Schmidt hammer to make small variations in the output to match the anvil reference reading. The range of this adjustment is about ±4 points.

Before modifying the Schmidt hammer, tests were conducted in a dry enviroment using the test anvil to evaluate the performance of the hammer and establish the repeatibility of the measurement. The rebound numbers for three different unmodified Schmidt hammers averaged 60 with a standard deviation less than 2.0. This agreed exactly with the reference rebound number on the test anvil.

After the Schmidt hammer was modified for underwater use, the average rebound number, obtained using the test anvil in a dry enviroment, dropped to 46.5, although the standard deviation remained about the same. This represented a decrease in the standard reference rebound number for the modified hammer of 23%. It was determined that the lower rebound numbers resulted from energy losses associated with the extension of the impact plunger. This reduces the useful operating range of the modified hammer compared to the standard Schmidt hammer. Therefore, low compressive

strength measurements will be limited by the effect of lower average rebound numbers. However, the lower rebound numbers can be normalized for direct comparison with standard Schmidt hammer data using the following relationship:

$$R = \frac{\sum r \times \text{Anvil No.}}{n \times R_a} = \frac{\sum r \times 60}{n \times 46} \qquad (1)$$

where: R = Corrected rebound number

r = Measured rebound numbers

n = Number of measurements

R_a = Rebound number obtained on anvil

This relationship was used to make comparisons between data obtained with the modified hammer and the standard Schmidt hammer during laboratory tests.

Laboratory measurements were taken on six different concrete blocks (10x12x24 inches) using the modified Schmidt hammer and two standard Schmidt hammers. The top of each block had a rough wood trowel finish and the remaining sides were smooth, cast surfaces. Each block was a single mix of concrete, except block six, which contained three different concrete mixes and was divided into areas 1, 2, and 3. (The concrete floor in the laboratory was also used as a test block.)

Dry measurements were taken with the three hammers on the top and sides of each block in the same general area. The average rebound numbers obtained from each block are presented in Table 3. The modified hammer data were normalized, using Equation 1, for direct comparison with the data obtained using the standard Schmidt hammers. Data from Table 4 obtained with the standard hammer (No. 1-8140) are compared against data obtained with the standard hammer (No. 2-8155) and the modified hammer (No. 8148) in Figure 12. The mean differences appear to be randomly distributed and are generally within the expected limits of ±20% for the Schmidt hammer.

Data obtained from the tops of the concrete blocks differed from the side measurements by as much as 44%. The rebound numbers were always much lower on the rough top surface than on the smooth cast-in-place sides. On blocks 3, 4, and 5, no readings were obtained from the top surface with the modified hammer because they were outside its operating range (too low). These data illustrate the effect of surface roughness on Schmidt hammer data. In actual field use, each measurement site must be thoroughly cleaned and smoothed in order to compare the results from one location with rebound numbers obtained at another point on the structure.

When the modified Schmidt hammer was initially tested submerged, the average rebound number obtained with the test anvil dropped to 45.2 and the standard deviation increased to 4.6. After practicing with the hammer underwater, the standard deviation of the readings dropped below 2.0 and the average rebound number increased to 46.1. This test demonstrated that the standard deviation of the readings could vary substantially even on the test anvil. Minor things such as keeping the hammer

centered on the anvil, cleaning the anvil surface, maintaining a constant hammer position, etc., affect the measurement and the operator must use a consistent technique to increase the repeatability of the readings. It is necessary for each operator to practice with the hammer to develop a consistent technique.

Measurements were taken underwater with the modified Schmidt hammer on the side of each test block in the same general area where the dry measurements were made. These data are tabulated in Table 4 along with the rebound numbers measured during the dry tests. Figure 13 is a plot of the dry versus wet data obtained with the modified Schmidt hammer. The rebound numbers obtained underwater tend to be higher than the comparable dry data, although they are still within the expected error band of ±20%. The exception was the test results from block No. 4, which were considerably lower. It was determined that the rebound numbers from block No. 4, obtained underwater, were not taken in the same area as the dry measurements. This accounts for the shift in the data since block No. 4 was made with very low strength ready-mix concrete and the uniformity varied significantly.

In summary, a Schmidt hammer was modified for underwater use and its use demonstrated in laboratory tests. The modification introduced an offset in the rebound data of 23% that limits the low compressive strength measurements compared to the standard hammer. After normalization, there were no significant differences between rebound numbers obtained with the modified hammer compared to the standard Schmidt hammer. The instrument can be used to rapidly survey concrete surface conditions to look for nonuniformity, provided the surface is adequately cleaned. A major redesign of the hammer will be required to remove the effect of lower rebound numbers that resulted from the initial modification.

ULTRASONIC TESTING

The transit time of high frequency sound waves through concrete can be used to assess its condition. Ultrasonic testing procedures for concrete have been standardized by ASTM Standard C-597 (Ref 10) and test equipment is available from commercial sources. Ultrasonic sound velocity tests were carried out on both laboratory test specimens and completed concrete structures. A detailed description of ultrasonic testing of concrete is presented in Reference 2 for terrestial applications.

Background

Ultrasonic testing of nonhomogeneous materials, such as concrete and timber, is significantly different than ultrasonic testing of homogeneous materials (metals). For example, when metals are tested ultrasonically, one objective is to detect internal flaws that send echoes back in the direction of the incident beam. These echoes are detected by a transducer that acts as both the transmitter and receiver. The position of the flaw can be determined from the measurement of the time taken for the pulse to travel from the surface to the flaw and back. This assumes a uniform sound velocity through the material being tested which is the case for metals. The thickness of metals is also measured in the same manner.

This approach cannot be applied to nonhomogeneous materials because echos are generated at the numerous boundaries of the different phases within these materials, resulting in a general scattering of the pulse energy in all directions. Also, the sound velocity through nonhomogeneous materials is not constant and depends on the material composition, density, and elastic properties. However, an average sound velocity can be measured and used to evaluate material composition and uniformity.

Measuring the average sound velocity in materials such as concrete requires using separate transmit and receive transducers to avoid the energy scattering problem. The sound velocity is calculated by measuring the time required to transmit over a known path length. The measurement of average sound velocity through concrete is recommended as a means to establish the uniformity of the concrete being tested (Ref 2). It is not recommended that average sound velocity be correlated with concrete compressive strength, but rather that it be used only as an indicator of concrete quality. Table 5 presents some suggested sound velocity ratings for concrete and for comparison includes an average sound velocity for water (Ref 2).

The two most important factors that affect the measurement of ultrasonic sound velocity through concrete are listed below and must be considered when making sound velocity measurements.

Concrete Surface Finish. The smoothness of the surface under test is important for maintaining good acoustical contact between the face of the transducer and the surface of the concrete. Cast surfaces are generally sufficient for routine testing and coupling agents such as silicone grease, water, etc. will help to improve coupling. Good acoustical coupling is necessary to obtain accurate sound velocity measurements.

Presence of Reinforcing Steel. Sound velocity measurements taken near steel reinforcing bars may be high because the sound velocity in steel is 1.2 to 1.9 times the velocity in concrete. When the axis of the rebar is perpendicular to the direction of propagation, the influence on sound velocity is generally small and if the quantity of reinforcement is small the correction factors are on the order of 1 to 4% depending on the quality of the concrete. If the axes of the reinforcing bars are parallel to the direction of propagation, reliable corrections are difficult to make and it is recommended that sound paths be chosen that avoids the influence of reinforcing steel. The derivation of correction factors to compensate for the effects of reinforcement on sound velocity measurements in concrete are covered in Reference 2 for both the perpendicular and parallel cases.

Three approaches for measuring sound velocity in concrete are illustrated in Figure 14. The most common method is direct transmission where the transducers are positioned on opposite sides of the test specimen and the longitudinal waves propagate directly toward the receiver. For indirect transmission, both transducers are placed on the same side of the concrete and energy scattered by discontinuities within the concrete is detected by the receive transducer. The strength of the pulse detected in this case is generally less than 5% of the strength detected for the same path length when direct transmission is used. Semi-direct transmission is not normally used because it is difficult to maintain a consistent or known path length.

Direct transmission of the ultrasonic pulse is the preferred approach for measuring the average sound velocity in concrete because this method provides maximum sensitivity with a well defined path length. Indirect (surface) transmission is used when only one surface of the concrete is accessible, such as a concrete retaining wall. This approach does not have a well defined path length and indicates primarily the quality of the concrete near the surface.

Equipment Description

The ultrasonic equipment used for these tests was the Model C-4899 V-Meter manufactured by James Instruments, Inc., shown in Figure 15. This instrument is representative of commercially available ultrasonic devices used for laboratory and field testing of concrete. It generates low frequency ultrasonic pulses and measures the time for them to pass from one transducer to the other through the material between them. The V-Meter displays the transit time directly on a digital readout. The overall time measurement range is 0.1 to 9,990 microseconds, in three selectable intervals, with a resolution of 0.1, 1.0, and 10.0 microseconds, depending on the selected interval. The accuracy of the time measurement is ±0.1 microseconds. The instrument can be operated from commercial power or a self-contained battery pack that provides 6 hours of continuous use. A detailed description of the Model C-4899 V-Meter and its operation can be found in Reference 11.

A pair of lead zirconate titanite (PZT-4) piezolectric transducers, operating at a frequency of 54 kHz, were used with the V-Meter. The piezoelectric elements were mounted in rugged stainless steel housings, modified for underwater operation. The coaxial cables connecting the transducers to the V-Meter were about 150 feet in length. A metal calibration bar was provided with the instrument to accurately set the zero time reference to compensate for the effects of cable length.

Laboratory Evaluation

The basic purpose of the laboratory tests was to evaluate the operation of the ultrasonic V-Meter for underwater use. Direct transmission data were collected to compare sound velocity measurements in dry concrete with measurements taken underwater. Indirect transmission was examined to evaluate the ability to detect cracks in concrete underwater. In addition, acoustical coupling effects were examined for both modes of transmission.

Good acoustic coupling is necessary in order to make accurate and repeatable sound velocity measurements. For dry concrete, the surface must be reasonably smooth and a coupling agent, such as silicone grease is placed between the transducer and the concrete surface to make good acoustical contact and transfer maximum energy. If a coupling agent is not used, the transmitted signal is severely attenuated at the interface boundary between the transducer and the concrete surface due to the acoustic impedance mismatch. This results in large errors for the measurement of the transit time of the acoustic signal. Water is a reasonably good coupling agent and provides a significant improvement over air, but it was not good enough to match the dry measurements that

used silicone grease as the coupling agent. The difference between the wet and dry measurements depended on the smoothness of the concrete surface. The smoother the surface the closer they matched. Consequently, to reduce the error between the wet and dry measurements, silicone grease was also used underwater to improve acoustic coupling.

The signal detection threshold of the V-Meter also causes erroneous transit time data to be recorded on the digital readout of the instrument. This happens when the amplitude of the first peak of the received signal is below the threshold voltage triggering level of the V-Meter. This effect is illustrated in Figure 16, taken from Reference 12, which also discusses this problem. When the instrument detects a following peak, this causes an apparent transit time increase of one-half wavelength or more. For example, if the sound velocity were 12,000 ft/sec in the concrete under test and the frequency being used is 54 kHz, the wavelength of the transmitted signal is about 2.7 inches. An error of one-half wavelength under these conditions, over a path length of 1 foot, results in an 11% error in measured sound velocity. A plot of the half-wavelength detection error as a function of path length and pulse velocity at 54 kHz is shown in Figure 17. This error is inversely proportional to the path length and the ultrasonic test frequency.

Indirect transmission is more prone to errors associated with the detection threshold and the degree of acoustic coupling than direct transmission because of the much lower signal strengths. Two actual signal waveforms shown in Figure 18 for indirect transmission further illustrate the problem. Both signals were transmitted through the same test block, over the same path length, but the coupling for the right waveform was much better than the left waveform as indicated by the received signal amplitude. The digital indication obtained from the V-Meter is shown on each waveform and indicates the detected peak. The difference in measured transit time was 29 microseconds, an error of approximately 20%. Therefore, during all acoustic measurements, silicone grease was used to improve acoustic coupling and the received signal was recorded on an oscilloscope to verify the digital readout from the V-Meter.

Sound velocity measurements were taken on five concrete test blocks (10x11x24 inches), both dry and submerged in water. Direct transmission was used and the data are tabulated in Table 6 for comparison. Blocks 1, 2 and 3 would be rated as "good" concrete while blocks 4 and 5 would be rated 'questionable' according to Table 5. The average sound velocity measured when the blocks were dry was slightly higher than the average sound velocity when the blocks were submerged. The standard deviation of the dry measurements is slightly lower than for the measurements taken underwater. The trend of slightly higher averages, coupled with lower standard deviations for the dry measurements compared to the same measurements taken underwater was attributed to better acoustic coupling. However, as expected, there are no significant differences in measured sound velocity between the wet and dry measurements.

Laboratory tests were conducted using indirect transmission to evaluate the ability of ultrasonics to detect cracks in concrete that are around 1/32 of an inch wide and of varing depth. Several test specimens, each with a different depth crack, were made for the evaluation. The depths of the simulated cracks varied from 0.5 to 2.25 inches deep and the measured direct sound velocity through each specimen averaged about

10,500 ft/sec, which indicates low strength concrete. Indirect measurements, however, did not indicate the simulated cracks in any of the test specimens during either the dry or wet tests. The calculated equivalent path length, based on the average sound velocity in the test specimen and the measured indirect time of flight, indicated the sound waves reflected off the back surface of the test block. The spacing between the transmit and receive transducers was maintained between 4 and 6 inches for these measurements. The test blocks should have been much larger in size to eliminate the effects of the reflected wave in order to draw conclusions from this series of tests.

Indirect measurements were also taken on a prestressed octagonal concrete pile that had cracks around its circumference in five different locations along its length, as shown in Figure 19. All of the cracks were clearly visible and appeared to go completely through the pile. One crack near the end of the pile was much wider than the others. This crack was measured to be around 0.025 to 0.030 inch wide at the surface on the face were the measurements were made. The other cracks were estimated to range from 0.001 to 0.010 inch wide on the same surface. The actual width of a crack is very difficult to quantify because of its highly irregular three dimensional shape, and these are very approximate values.

Indirect transit times were measured as a function of position along the prestressed pile and they are plotted in Figure 19 for a 6- and 8-inch path length. The positions of the transmit and receive transducers are indicated for each measurement, in addition to the location of the cracks. These data were taken with the pile dry and except for the large crack located at position number one, there was no apparent change in measured transit time for either path length due to the cracks. For the measurements taken across crack number one, the transit time for the 8-inch path length increased by 36% and for the 6-inch path length, the transit time increased by 68%. The increase in transit time for the sound pulse, due to the increased path length around the crack, can be used as a good indicator of the presence of large cracks in concrete but should not be used to estimate the depth of the crack. The transit time measurements did not change when the cracks were filled with water.

In summary, ultrasonics can be used to categorize concrete by measuring the sound velocity in the material using direct transmission. Good acoustic coupling will enable accurate time measurements to be made for calculating sound velocity. Direct and indirect transmission can also be used to compare the general condition of the concrete from one location to another on the same structure, assuming the concrete mix is the same. Indirect transmission normally should not be used to obtain sound velocity measurements for categorizing or rating concrete because of the poorly defined sound path length. Indirect transmission appears to detect deep cracks (on the order of 0.030 inch wide) in concrete, but it did not detect other cracks that were much narrower but still clearly visible.

FIELD TEST RESULTS

After the laboratory tests were completed, the R-Meter, Schmidt hammer, and V-Meter were used to collect data during a recent inspection (August 1984) of Pier J/K in San Diego, California (Ref 13). Ultrasonic testing was performed using the V-Meter and data were collected with the Schmidt hammer on selected piles to help assess the performance of these instruments in the field. The R-Meter was also used to collect data for assessing its performance. All of the instruments worked well during the field evaluations.

Background

Pier J/K is an old concrete, pile-supported, waterfront structure, located at the North Island Naval Air Station in San Diego. The pier is supported by 791 piles and was built in three phases: 1921, 1930, and 1958. The 1921 construction (about 45% of the pier) used a combination of 14- and 18-inch square conventionally reinforced piles. The 1930 construction (also about 45% of the pier) used 16-inch square conventionally reinforced piles. The remaining 10% of the pier was constructed in 1958 and it is supported on 16-inch octagonal prestressed piles.

In 1981, this pier was inspected by Blaylock-Willis and Associates of San Diego, under contract to the Ocean Engineering and Construction Project Office (FPO-1), Naval Facilities Engineering Command (Ref 14). During this inspection, moderate to severe sulphate deterioration was observed in all the concrete piles constructed in 1921 and 1930. The inspection contractor speculated that Type I cement was used in those piles; this type of cement has not been considered appropriate for salt water use since around 1940. This inspection recommended that the pier live load be restricted to 100 pounds per square foot and truck cranes with capacities over 15 tons be prohibited. The contractor estimated the remaining useful life to be no greater than 5 years.

In 1984, FPO-1 again contracted with Blaylock-Willis, at the request of the Naval Air Station, to reassess the condition of Pier J/K and update their recommendations. During this inspection, NCEL personnel worked with the contractor and FPO-1 to obtain NDT measurements on some of the deteriorated concrete piles. Data were also collected on a few of the 1958 piles (which were in excellent condition) for comparison. The overall results of this inspection confirmed the earlier findings.

Before taking any NDT measurements, selected piles were thoroughly cleaned by the contractor using the NCEL's high pressure water jet cleaning system in conjunction with a rotary abrading tool attachment ("Whirl Away"). Both the water jet and rotary abrading tool removed some of the deteriorated surface area from the piles exhibiting extensive sulfate attack. Where this happened, it was not possible to obtain good NDT measurements using ultrasonics or the Schmidt hammer because of the surface roughness. (Relatively smooth surface areas are required to obtain good ultrasonic and Schmidt hammer data.)

Test Results

R-Meter. The modified R-Meter was used to measure the depth of concrete cover over the rebar in five different piles from the 1930 construction group. The data obtained with the R-Meter are presented in Table 7 and a cross section view of the 1930 piles is shown in Figure 20. The rebar's configuration in the pile varied depending upon its location in the pile as shown in Figure 20. The amount of concrete cover was measured by positioning the probe of the instrument directly over the No. 6 rebar for measurements near the bottom of the pile and over the No. 7 rebar for the measurements taken near the top of the pile. A water depth reading was obtained at each measurement location.

A very good peak reading was obtained on the R-Meter when the probe was directly over the No. 6 rebar on the lower portion of the pile. The measured depth of concrete cover over the No. 6 rebar averaged 1.89 inches thick. This number is in error by a small amount due to the effect of adjacent parallel rebar. The spacing between the rebars would have to be about 7.5 inches to eliminate this effect instead of the 5.5 inches indicated in Figure 20. The amount of error is difficult to quantify and the actual depth of concrete cover is thicker than the indicated depth. The actual depth was probably between 2 and 2.5 inches deep.

When the probe was used near the top of the pile, a narrow peak reading could not be obtained and it was impossible to differentiate between the two adjacent No. 7 rebars. The effect of the parallel rebar was very apparent in these measurements and it strongly influenced the readings. The average depth of the concrete cover measured near the top of the piles was 4.64 inches. The actual depth of cover over the rebar was greater than the measured amount. The data indicate a large difference between the construction plans as shown in Figure 20 and what was actually built.

When taking measurements of concrete cover over the rebar in concrete piles, the data usually will be influenced by the effect of closely spaced rebar. In some cases, it will not be possible to obtain narrow peak readings that indicate the actual location of the rebar due to the narrow spacing of the rebar with respect to the depth of concrete cover. The actual depth of concrete cover, however, will always be greater than the measured amount. Reducing the effects of closely spaced parallel rebar would require a major redesign of the instrument to alter the shape of the generated magnetic field.

The field tests demonstrated that divers were able to use the instrument with very little training. The field tests also demonstrated that the instrument would be more effective if the diver collected the data after orienting the probe rather than depending upon a verbal communication link to the surface operator. A reel to handle the instrumentation cables would also be benefical.

Schmidt Hammer. The modified Schmidt hammer was used to measure the concrete surface hardness of selected piles from the 1930 and 1958 construction groups to evaluate its performance in the field. The data obtained with the modified Schmidt hammer are presented in Table 8 for the two different pile groups and include the anvil calibration data before and after the measurements.

Once a region on the pile was sufficiently cleaned, data could be taken with the Schmidt hammer as rapidly as the diver could operate the device. Operating the hammer was very simple for the diver; he only had to press the plunger of the hammer firmly against the pile until an impact was felt or heard. The diver then moved the hammer back away from the surface to automatically recock it, then the hammer was simply pressed against the surface again to take another measurement. This sequence was continually repeated and required less than 30 seconds to get 12 readings in any one area of the pile.

The data were taken in regions near the top and bottom of each pile. These areas were previously cleaned and smoothed with a small carborundum stone by the diver. Twelve readings were taken at each location, then the high and low values were dropped before averaging. Twelve readings were not obtained in two locations for the 1930 piles numbered 93F and 93H because the surface was very soft and some of the readings did not register, since they were outside the range of the instrument. This soft surface condition is indicated by the limited data that were obtained. Also, only six readings were collected on pile 88H from the 1958 group because some fouling remained on the pile, creating a rough surface. The limited data from pile 88H did indicate a surface condition comparable to the other 1958 piles.

The average uncorrected rebound number of the data collected from the 1958 pile group was 37.9, which is 23% higher than the average uncorrected rebound number of the 1930 pile group. This indicates a much softer surface condition on the piles from the 1930 group and would normally indicate a lower strength concrete. This finding of a soft surface condition supports the conclusions from the previous inspection and indicates that the Schmidt hammer can be used to survey the surface condition of concrete underwater.

In summary, the field test demonstrated that divers can easily use the Schmidt hammer underwater to obtain valid data on concrete surface hardness. The surface must be properly cleaned, however, to obtain consistent data.

V-Meter. The V-Meter was used to collect ultrasonic data on selected piles from the 1930 and 1958 construction groups, using both direct and indirect transmission methods. For direct transmission, a pair of calipers were used by the diver to measure the transmission path length. The path length for indirect transmission was fixed at 10 inches between the centers of the transmit and receive transducer faces. Silicone grease was used on the face of each transducer to improve acoustic coupling. No fixtures were built to hold the transducers for direct measurements, the diver merely pressed them firmly against the concrete surface while the measurement was made. A small guide block was used to maintain the 10-inch spacing for the indirect measurements.

The received acoustic signal was displayed on an oscilloscope and the pulse transit time was measured from the oscilloscope display to reduce detection threshold errors. If the received signal was a poor quality waveform, which was generally the case for the indirect measurements, several signals would be collected and averaged to obtain an improved signal-to-noise ratio. The received signal was also digitized and stored on magnetic tape for later analysis as required.

The ultrasonic data obtained using direct transmission through the piles are presented in Table 9. The table lists the pile, pulse transit time, path length, and calculated sound velocity through that particular section of the pile. Data were collected on piles in the 1930 and 1958 construction groups and a few measurements were also taken on the concrete pile caps in bents 9 and 10.

The data for the 1930 piles were divided into two groups. The piles from bents 8 and 9 were more severely damaged from sulfate attack than the piles from bent 93. The average sound velocity data for both groups of piles, however, was approximately the same and quite high (around 15,000 fps). All of these piles would be rated "good" to "excellent" using the suggested pulse velocity ratings for concrete presented in Table 5. The standard deviation of the measurements from the piles in bent 93 was lower than for the other group of piles from bents 8 and 9. The higher standard deviation was a direct result of a rougher surface condition on those piles.

The direct transmission data for the 1958 piles given in Table 9 are not significantly different from the data collected on the 1930 piles. The mean sound velocity was higher (around 15,600 fps) by 4% and the standard deviation was smaller. All of the 1958 piles would be rated as "excellent" according to ratings from Table 5. From a visual inspection, these piles appeared to be in excellent shape and the Schmidt hammer data also indicated a much harder surface compared to the 1930 piles.

A comparison of the direct transmission data for the two age groups of piles indicates no significant difference in the mean sound velocity measurements. This indicates that the effects of the sulfate attack occurring on the 1930 piles does not penetrate into the concrete enough to significantly alter the average sound velocity. In addition, these measurements indicate that the bulk compressive strength of the 1930 piles is quite high and comparable to the prestressed 1958 piles.

Additional measurements should have been made near the top of the 1930 piles, above the waterline, to obtain reference measurements but at the time of the inspection this was not possible due to logistics problems. A reference measurement would have provided information to better estimate the depth of the sulfate attack in the concrete. A core sample from the piles at the point of measurement is required to accurately define the extent of the sulfate attack.

Direct transmission data were collected in several locations on the pile caps over bents 9 and 10. Initially it was assumed these data could be used as a reference sound velocity, but it turned out that the pile caps were made from a different mix of concrete. The data indicated a much lower sound velocity compared to the measured sound velocity through the concrete in the piles. This is an indication of lower compressive strength; however, the concrete would still be rated as "good". The standard deviation of these measurements was high, which indicates some variability in the concrete, because the concrete surface was smooth and good acoustic coupling was obtained for these measurements.

In general, the direct transmission data do not indicate any significant difference between the concrete in the 1930 and 1958 pile groups. If the sulfate attack in the 1930 piles had only penetrated 1 inch into the concrete, for example, this would reduce the measured

sound velocity about 10% assuming the sound velocity through the damaged concrete dropped to 8,000 ft/sec. If reference measurements could have been made near the top of the piles, this change might have been detected. As it stands, the average sound velocity through the 1930 piles appears to indicate sound concrete when compared to similiar data from the 1958 piles that are not effected by the sulfate attack.

Indirect ultrasonic measurements were made on the same piles as the direct measurements and at essentially the same locations. It was assumed that comparison of data from the two different pile groups would show some indication of the sulfate attack occurring on the 1930 piles. The data collected from the indirect measurements are tabulated in Table 10. The table lists the pile, general location of the measurement, measured pulse transit time over the fixed 10-inch path length, and general comments concerning the shape of the waveform displayed on the oscilloscope. Acoustic coupling was much more critical for these measurements compared to the direct measurements because of the reduced signal levels at the receive transducer.

The average indirect transit time for the ultrasonic pulse in the 1930 piles was only about 1% higher than the average transit time for the 1958 piles. If only the data from "good" waveforms are considered, the difference is around 3.5%. From the direct sound velocity measurements, a difference of about 4% would be expected in the indirect measurements, which is the case if the data for the attenuated waveforms are dropped. Dropping these data has the most effect on the average for the 1958 piles. The 72-microsecond transit time for the top of pile 90H compared to 64 microseconds at the bottom corresponds to a half-wavelength difference in path length at 54 kHz. Therefore, these data do not show any significant differences in the ultrasonic pulse transit time through the 1930 piles compared to the 1958 piles. Thus, indirect ultrasonic measurements did not detect the sulfate attack occurring on the 1930 piles.

Indirect measurements were also taken on the pile caps in the same location as the direct measurements. The indirect transit times were quite large compared to the indirect measurements taken on the piles. This can be illustrated by calculating an apparent sound velocity using 10 inches as the path length for the indirect measurements. For the 1930 piles this would be an average apparent sound velocity of 12,350 ft/sec, which can be compared to the direct measurement of 14,925 ft/sec, a decrease of about 17%. Calculating the same apparent sound velocity for the indirect measurements on the pile caps results in a value that is 45% lower than the direct measurement. This indicates that a rating system could be developed and applied to indirect measurements on concrete that has only one side accessible, even though a path length is not very well defined.

In summary, neither the direct or indirect sound velocity measurements clearly indicated the sulfate attack on the piles in the 1930 group. The direct measurements indicated very sound concrete and did not indicate the sulfate attack (comparing data from the 1930 and 1958 pile groups). Likewise, there was no significant difference in the data from the two pile groups for the indirect measurements. Good reference readings obtained above the waterline on each pile would have provided more information.

Making ultrasonic measurements on concrete underwater was not difficult and required very little diver training. The only real precautions to observe are: (1) make sure the measurement area is thoroughly cleaned, and (2) a good acoustic coupling is obtained. The actual measurement is very straight forward and easily performed by divers.

In general, the data obtained in the field tests demonstrate the importance of combining Schmidt hammer and ultrasonic testing when inspecting concrete underwater. It is probable the sulfate attack has not penetrated very deep into the piles; consequently the effect on sound velocity through the pile would not be significant. The Schmidt hammer tests, however, did detect a much softer surface condition on the piles from the 1930 group compared to the 1958 piles, which was an indication of the sulfate attack. The extent of the sulfate attack into the piles could be confirmed by taking several core samples and performing a chemical analysis.

CONCLUSIONS AND RECOMMENDATIONS

1. A commercially available magnetic rebar locator was successfully modified for underwater use. The R-Meter can be used to determine the location of rebar in concrete, measure the depth of concrete cover, and determine the size of the rebar. Laboratory and field tests of the instrument demonstrated that there was no effect on the output data after modification for underwater use.

2. A standard Schmidt hammer was successfully modified for underwater use and can be used to rapidly survey concrete surface hardness. The modification, however, introduced an offset in the rebound data of 23% compared to the same data obtained with an unmodified Schmidt hammer. Data can be normalized for direct comparison, but the offset does limit the low compressive strength measurements because the lower detection threshold was changed due to the hammer modifications.

3. Ultrasonics can be used successfully underwater to help evaluate the condition of concrete structures. A commercially available instrument was easily modified for underwater use. Laboratory and field tests of the instrument demonstrated there was no effect on the output data after modification. Both direct and indirect transmission methods can be used in the field to evaluate the uniformity of concrete and obtain a general condition rating. Cracks in concrete greater than 0.030 inches wide were detected in laboratory tests.

4. NCEL recommends that a prototype concrete inspection system be developed and evaluated for use by Navy UCT personnel and others to help inspect concrete structures underwater. This system should be comprised of an R-Meter, a Schmidt hammer, ultrasonic test equipment, and a common data acquisition system. The prototype Schmidt hammer should be designed to eliminate any data offset and retain the standard data range of the instrument, thus providing a direct correlation with standard Schmidt hammer test results. The prototype ultrasonic inspection system should be designed to minimize acoustic coupling effects and increase the measurement reliability. A diver operated mechanical device should be developed

to hold the transducers and measure the transmission path length automatically. A common data acquisition system should be developed to interface the three instrumentation systems mentioned above and discussed in this report. This system would collect and output data from each instrument for field evaluation and later analysis.

5. An integrated systems approach for the underwater inspection of concrete structures, as shown in Figure 21, is further recommended. This approach uses the underwater cleaning system developed by NCEL (Ref 15) as a key element, in addition to the three instruments discussed in this report. The cleaning system is used to clean the concrete for Level II and Level III inspections and provide a hydraulic power source to take core samples if required. The three instrumentation systems utilize a common data output and analysis system. Information from the inspection would indicate if concrete cores were required to complete the analysis of the structure. A rebar corrosion detection system, under development by NCEL (Ref 16), should be integrated into the underwater inspection system and, if possible, included as part of the R-Meter design.

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Table 1. Level of Inspection and Damage Detected for Underwater Concrete Structures

	Purpose	Defects
Level I	General visual to confirm as-built condition and detect severe damage	Severe mechanical or ice damage
Level II	Detect surface defects normally obscured by marine growth	Surface cracking due to mechanical overload
		Severe corrosion of rebar
		Spalling of concrete surface
Level III	Detect hidden and incipient damage	Location of rebar
		Depth of concrete cover over rebar
		Incipient corrosion of rebar
		Internal voids
		Change in material strength

Table 2. R-Meter Readings from Test Blocks in Inches of Concrete Cover Before Modification and After Modification with the Probe Submerged in Water

Test Block	Position	Rebar Size	R-Meter Readings (inches)		Difference (in.)
			Before Mod.	After Mod. (submerged)	
A	1	No. 3	1-7/8	1-7/8	--
	2		1-3/4	1-3/4	--
	3		3-1/4	3-1/4	--
	4		3-1/8	3-3/16	+1/16
B	1	No. 4	1-7/8	1-7/8	--
	2		2-1/8	2-1/8	--
	3		3-3/8	3-1/2	+1/8
	4		3-3/4	3-7/8	+1/8
C	1	No. 6	1-3/4	1-3/4	--
	2		2-1/8	2-1/8	--
	3		3-5/8	3-3/4	+1/8
	4		3-3/4	3-7/8	+1/8
D	1	No. 7	1-1/4	1-1/4	--
	2		1-5/8	1-3/4	+1/8
	3		3-3/4	3-3/4	--
	4		3-7/8	4	+1/8

Table 3. Schmidt Hammer Data Comparison - Dry Tests

Concrete Test Block	Schmidt Hammer Data			Comparison					
	Hammer No. 1-8140 (Avg/S.D.)	Hammer No. 2-8155 (Avg/S.D.)	Mod. Hammer No. 8148 (Avg/S.D.)	1 - 2		1 - M.H.		2 - M.H.	
				Δ	%	Δ	%	Δ	%
No. 1-side	30.5/2.4	32.3/3.17	32.8/4.9	-1.8	-6	-2.3	-8	-0.5	-2
No. 1-top	28.6/3.3	29.4/3.2	24.0/3.1	-0.8	-3	4.6	16	5.4	18
No. 2-side	32.2/2.4	27.5/3.4	29.5/4.8	4.7	15	2.7	8	-2	-7
No. 2-top	19.8/1.8	18.9/3.6	16.9/3.3	0.9	5	2.9	15	2.0	11
No. 3-side	31.5/3.0	27.1/2.8	24.2/1.8	4.4	14	7.3	23	2.9	11
No. 3-top	17.7/2.0	18.9/3.5	*	-1.2	-7	--	--	--	--
No. 4-side	20.0/2.1	15.5/1.9	19.4/4.0	4.5	23	0.6	3	-3.9	-25
No. 4-top	13.0/3.7	14.9/3.0	*	-1.9	-15	--	--	--	--
No. 5-side	16.3/1.8	15.9/3.7	14.2/1.1	0.4	2	2.1	13	1.7	11
No. 5-top	13.0/1.5	12.6/2.4	*	0.4	3	--	--	--	--
No. 6-Area 1	32.9/1.3	32.6/1.6	33.9/3.4	0.3	1	-1	-3	-1.3	-4
No. 6-Area 2	26.5/1.8	28.8/3.6	30.5/5.1	-2.3	-9	-4.0	-15	-1.7	-6
No. 6-Area 3	33.8/2.8	33.2/3.1	37.7/4.5	0.6	2	-3.9	-12	-4.5	-14
No. 7-Floor	43.7/2.7	42.4/3.1	40.6/6.6	1.3	3	3.1	7	1.8	4
			Number of Data Points:	n = 14		n = 11		n = 11	
			Average Difference:	$\bar{x}$ = 2%		$\bar{x}$ = 4.3%		$\bar{x}$ = -0.3%	
			Standard Deviation:	s = 10		s = 12.4		s = 12.8	

*Outside operating range (too low).

Table 4. Modified Schmidt Hammer Data - Dry vs. Wet

Concrete Test Block	Mod. Hammer - 8148		Comparison	
	Dry Avg/S.D.	Wet Avg/S.D.	Wet-Dry Δ	W-D/W %
No. 1	32.8/4.9	38.1/3.3	5.3	14
No. 2	29.5/4.8	33.3/7.2	3.8	11
No. 3	24.2/1.8	28.0/5.4	3.8	14
No. 4	19.4/4.0	13.7/2.6	-5.7	-42
No. 5	14.2/1.1	16.0/2.1	1.8	11
No. 6-Area 1	33.9/3.4	36.4/4.9	2.5	7
No. 6-Area 2	30.5/5.1	31.5/4.6	1.0	3
No. 6-Area 3	37.7/4.5	41.0/5.5	3.3	8

Table 5. Ultrasonic Sound Velocity Ratings for Concrete

Sound Velocity		General Condition Rating
ft/sec	m/sec	
>15,000	>4,575	Excellent
12,000-15,000	3,660-4,575	Good
10,000-12,000	3,050-3,660	Questionable
7,000-10,000	2,135-3,050	Poor
<7,000	<2,135	Very Poor
4,860	1,480	Water

Table 6. Comparison of Direct Transmission Sound Velocity Data

Concrete Test Block	Average Sound Velocity (ft/sec)				$\frac{\text{Dry-Wet}}{\text{Dry}} \times 100$
	Dry		Wet		
	Mean	Std. Dev.	Mean	Std. Dev.	
No. 1	12,900	160	12,820	140	0.6%
No. 2	12,720	220	12,600	470	0.9%
No. 3	12,510	260	12,690	200	-1.4%
No. 4	10,810	210	10,760	270	0.5%
No. 5	10,980	85	10,850	120	1.2%

Table 7. R-Meter Measurements on Selected Piles from Pier J/K, Naval Air Station, North Island, San Diego, CA

Pile	Location/ Depth (ft)	Rebar Size	Measured Concrete Cover (inches)
93D	Top/1.3	No. 7	4.6
93D	Bot/16.8	No. 6	1.9
93E	Top/1.5	No. 7	4.4
93E	Bot/15.7	No. 6	2.0
93F	Top/0.8	No. 7	4.7
93F	Bot/16.1	No. 6	2.0
93G	Top/1.0	No. 7	4.8
93G	Bot/17.5	No. 6	1.7
93H	Top/1.0	No. 7	4.7
93H	Bot/15.0	No. 6	1.9

Table 8. Schmidt Hammer Data - Pier J/K

Pile Group	Pile Number	Number of Readings	Average Rebound Number	Standard Deviation	Comments
1958	88H	10	33.7	6.1	Near top
	88H	6	39.1	5.6	Near bottom
	90G	10	37.8	14.8	Near top
	90G	10	33.2	5.7	Near bottom
	90H	10	41.5	9.1	Near top
	90H	10	42.3	5.0	Near bottom
$\bar{x}$			37.9		
S.D.			3.8		
1930	93E	10	31.0	4.2	Near top
	93E	8	16.6	4.8	Near bottom
	93F	10	39.3	2.8	Near top
	93F	10	32.4	7.3	Near bottom
	93F	10	32.4	5.8	Near bottom
	93H	10	36.6	11.7	Near top
	93H	6	14.9	3.3	Near bottom
	93G	10	31.0	6.8	Near top
	93G	10	32.0	7.3	Near bottom
	93D	10	32.0	8.8	Near top
	93D	10	23.8	10.6	Near bottom
$\bar{x}$			29.3		
S.D.			7.7		
Calibration Anvil		10	48.9	2.8	Before test
		10	49.4	1.1	After test

Table 9. Ultrasonic Data from Pier J/K - Direct Transmission

(a) Individual Pile Data

Pile Group	Bent	Pile	Transmission Time (μsec)	Path Length (in.)	Sound Velocity (fps)	Comments
1930	8	H	89	16.50	15,450	--
	9	D	91	16.00	14,650	--
	9	F	95	16.00	14,035	--
	9	F	90	16.00	14,815	--
	9	H	88	16.25	15,390	--
	9	H	86	16.25	15,750	--
1930	93	D	90	16.25	15,050	--
	93	D	87	16.25	15,565	--
	93	D	89	16.25	15,215	--
	93	E	93	16.25	14,560	bottom
	93	E	93	16.25	14,560	bottom
	93	E	93	16.25	14,560	top
	93	F	87	16.12	15,445	top
	93	F	93	16.25	14,560	bottom
	93	G	90	16.25	15,050	top
	93	G	90	16.25	15,050	bottom
	93	H	93	16.25	14,560	bottom
1958	90	G	87	16.25	15,565	top
	90	G	86	16.50	15,990	bottom
	90	H	86	16.25	15,745	top
	90	H	86	16.25	15,745	bottom
	90	H	86	16.25	15,745	bottom
	92	H	88	16.00	15,505	bottom
	92	H	86	16.00	15,150	top
Pile Caps (Dry)	9	H	110	18.00	13,640	Data taken on pile caps near piles indicated
	9	H	106	18.00	14,150	
	9	H	111	18.00	13,515	
	10	H	116	18.50	13,290	
	10	H	113	18.50	13,643	
	10	H	97	14.25	12,240	

continued

Table 9. Continued

(b) Overall Sound Velocity (fps) Data

Pile Group	No. of Piles	Sound Velocity (ft/sec)--					
		Avg	S.D.	Minimum	Maximum	Difference	%
1930, Bents 8&9	7	15,015	633	14,035	15,750	1,715	11.4
1930, Bent 10	11	14,925	384	14,560	15,565	1,005	6.7
1958	7	15,635	265	15,150	15,745	595	3.9
Pile Caps (Dry)	6	13,413	640	12,240	14,150	1,910	14.0

Table 10. Ultrasonic Data from Pier J/K - Indirect Transmission

(a) Individual Pile Data

Pile Group	Pile	Location	Transmission Time (μsec)	Comments
1930-Path Length 10 in. (Bents 8&9)	8H	--	64	Good waveform
	9D	--	68	Good waveform
	9H	--	66	Good waveform
1930-Path Location 10 in. (Bent 93)	93D	top	67	Good waveform
	93D	top	68	Good waveform
	93E	top	68	First 2 cycles attenuated
	93E	bottom	64	Good waveform
	93E	bottom	75	First 2 cycles attenuated
	93F	top	74	First 2 cycles attenuated
	93F	bottom	68	--
	93G	top	65	First 2 cycles attenuated
	93G	bottom	66	Good waveform
	93G	bottom	66	Good waveform
	93H	top	64	Good waveform
	93H	top	65	Good waveform
	93H	bottom	68	First 2 cycles attenuated
1958	90H	top	72	First 2 cycles attenuated
	90H	top	72	First 2 cycles attenuated
	90H	bottom	64	Good waveform
	90H	bottom	64	Good waveform
	92H	top	62	Good waveform
	92H	bottom	64	Good waveform
Pile Cap (dry)	9	--	90	Data taken on pile caps near piles indicated
	9	--	123	
	10	--	118	
	10	--	119	
	10	--	120	

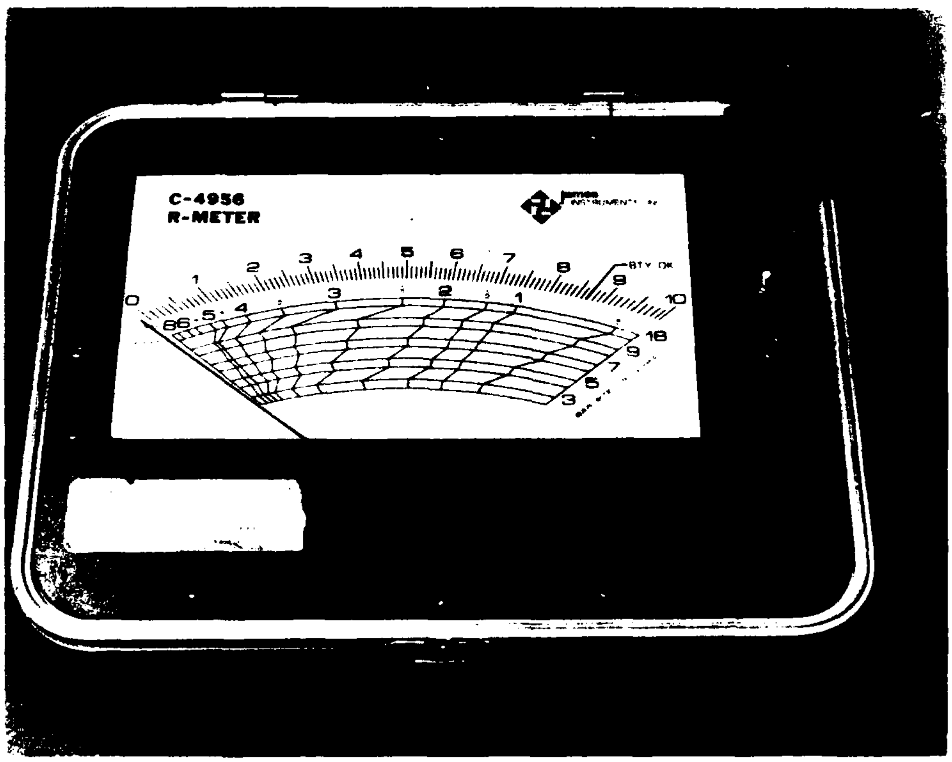
continued

Table 10. Continued

(b) Overall Indirect Transmission Time

Pile Group	No. of Piles	Indirect Transmission Time (μsec)					
		Avg	S.D.	Minimum	Maximum	Difference	%
1930-Path Length 10 in. (Bents 8&9)	3	66.0	--	--	--	--	--
1930-Path Length 10 in. (Bent 93)	13	67.5	3.43	64	75	11	15.8
1958	6	66.3	4.46	62	72	10	14.9
Pile Cap (dry)	5	114.0	13.5	90	123	33	31.4

(a) General view of R-Meter.



(b) Closeup view of meter readout.

Figure 1. R-Meter, Model C-4956.

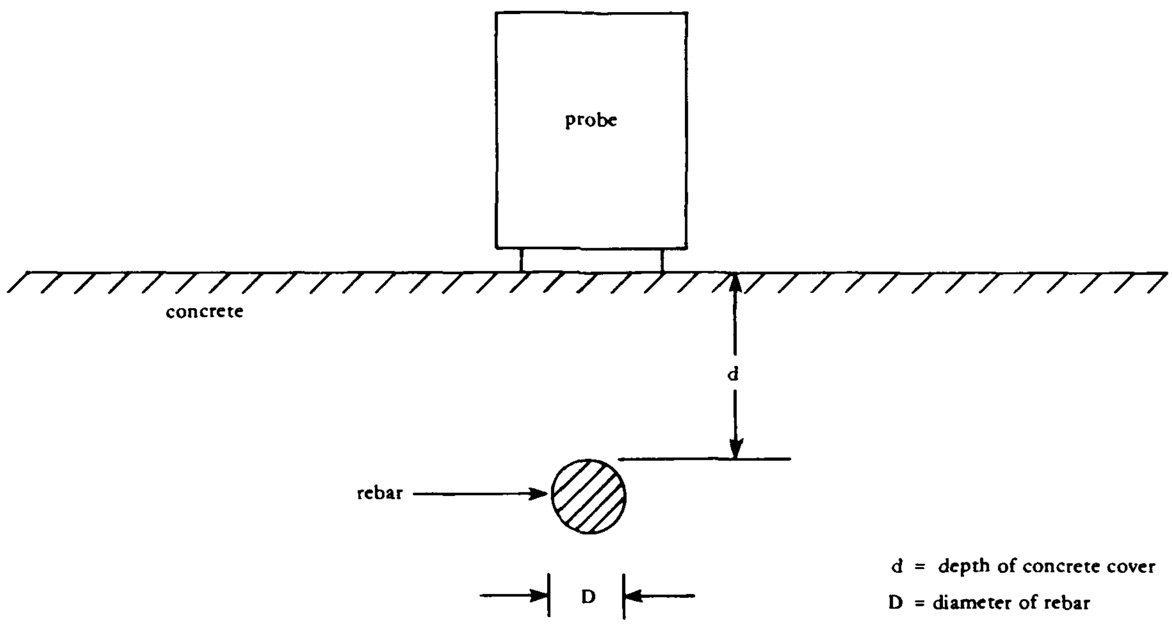


Figure 2. Diagram illustrating measurement of concrete cover using R-Meter.

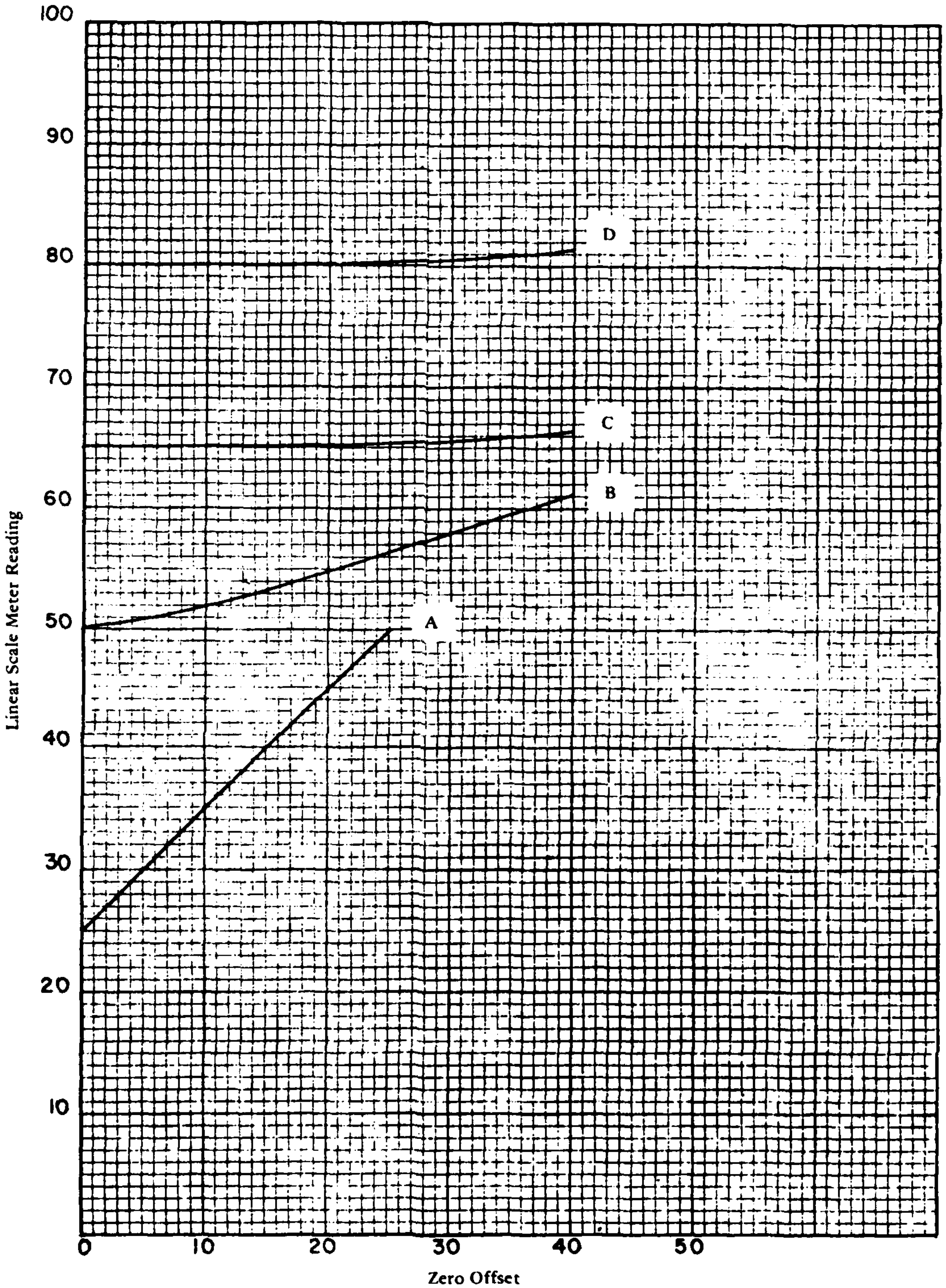


Figure 3. Effects of zero setting errors.

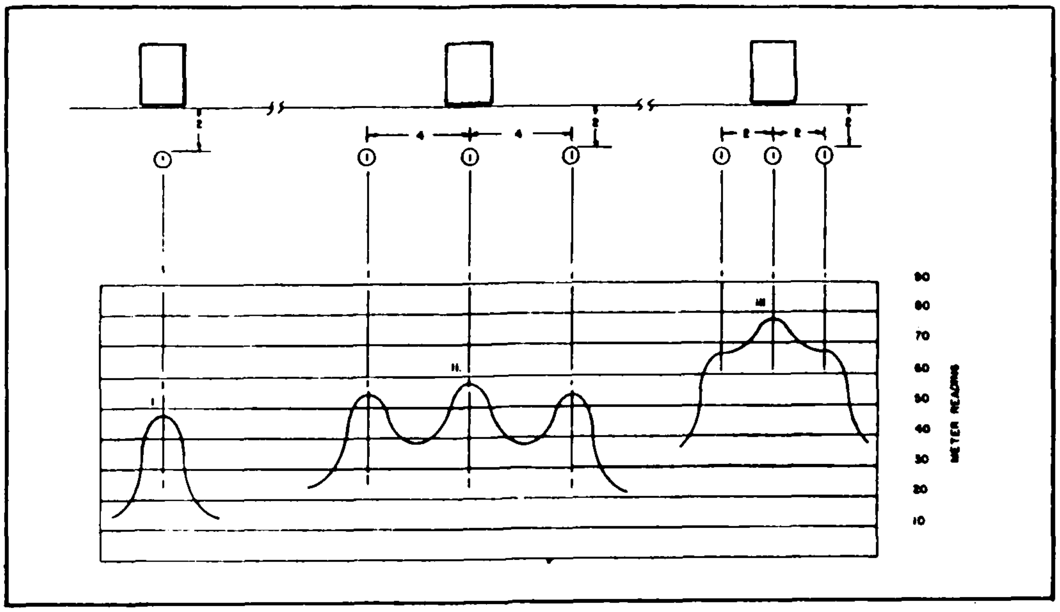
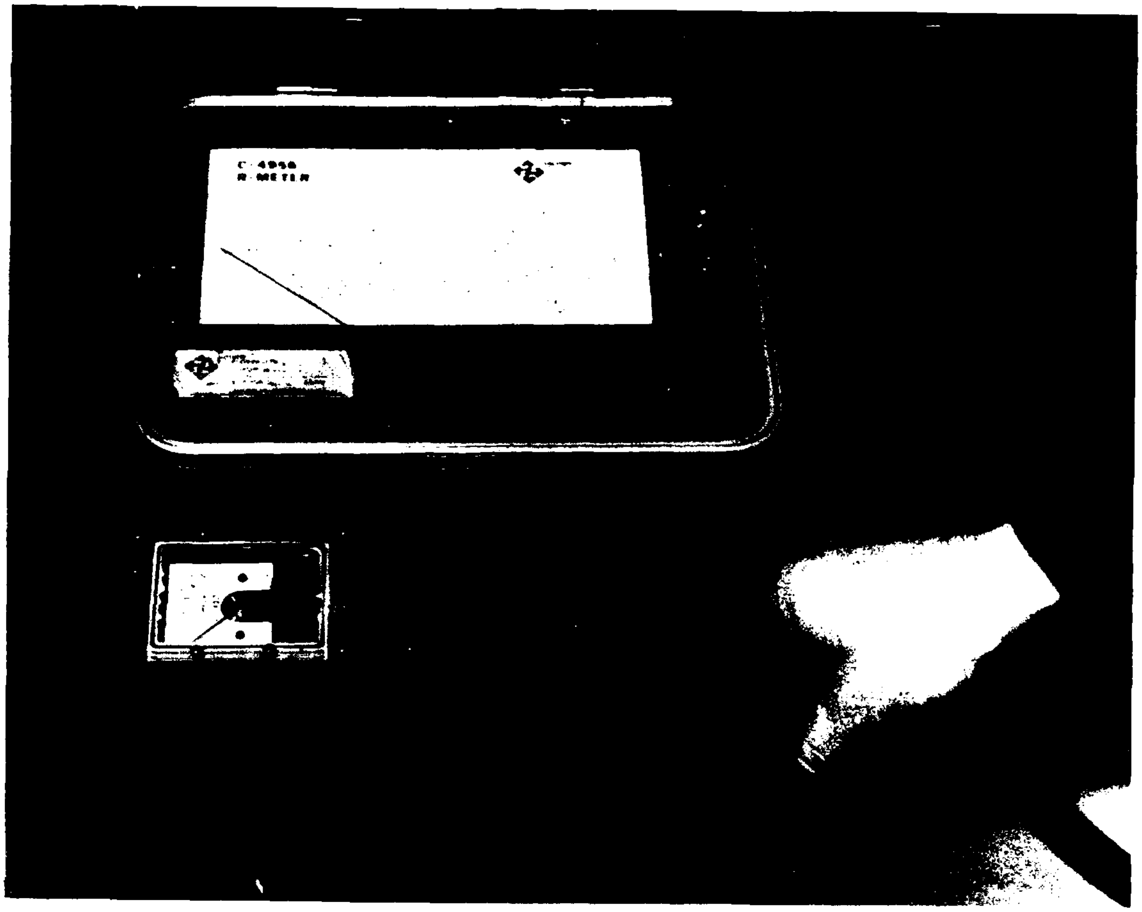
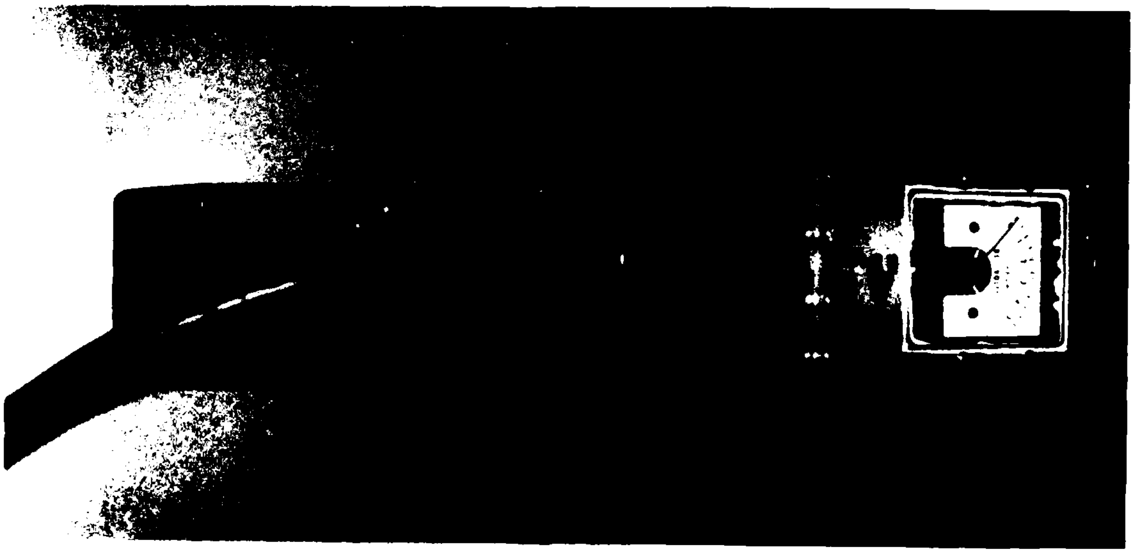


Figure 4. Diagram illustrating the effects of parallel one-inch-diameter rebar located two inches below the surface.



(a) General view of modified R-Meter.



(b) Closeup view of test probe.

Figure 5. R-Meter modified for underwater use.

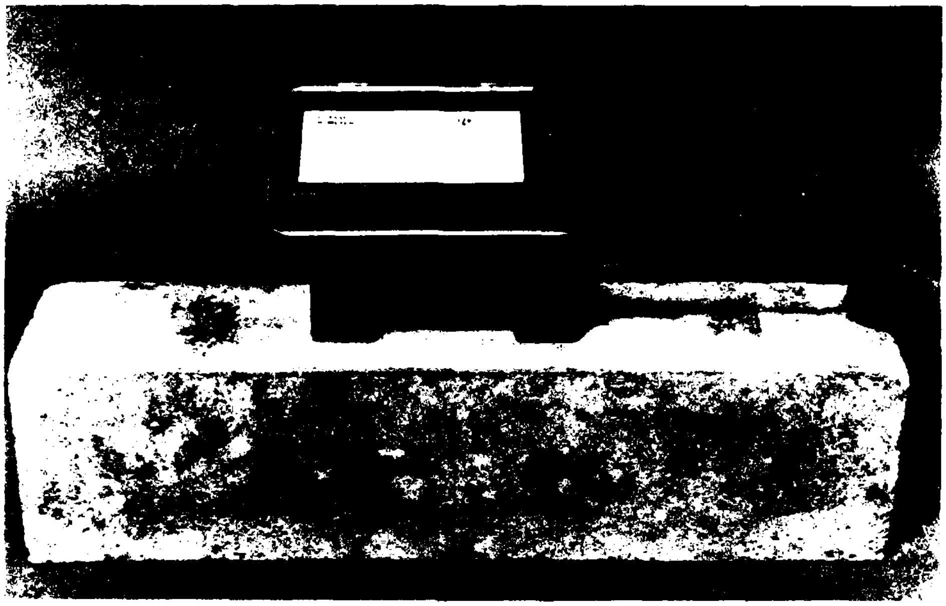


Figure 6. R-Meter on test block.

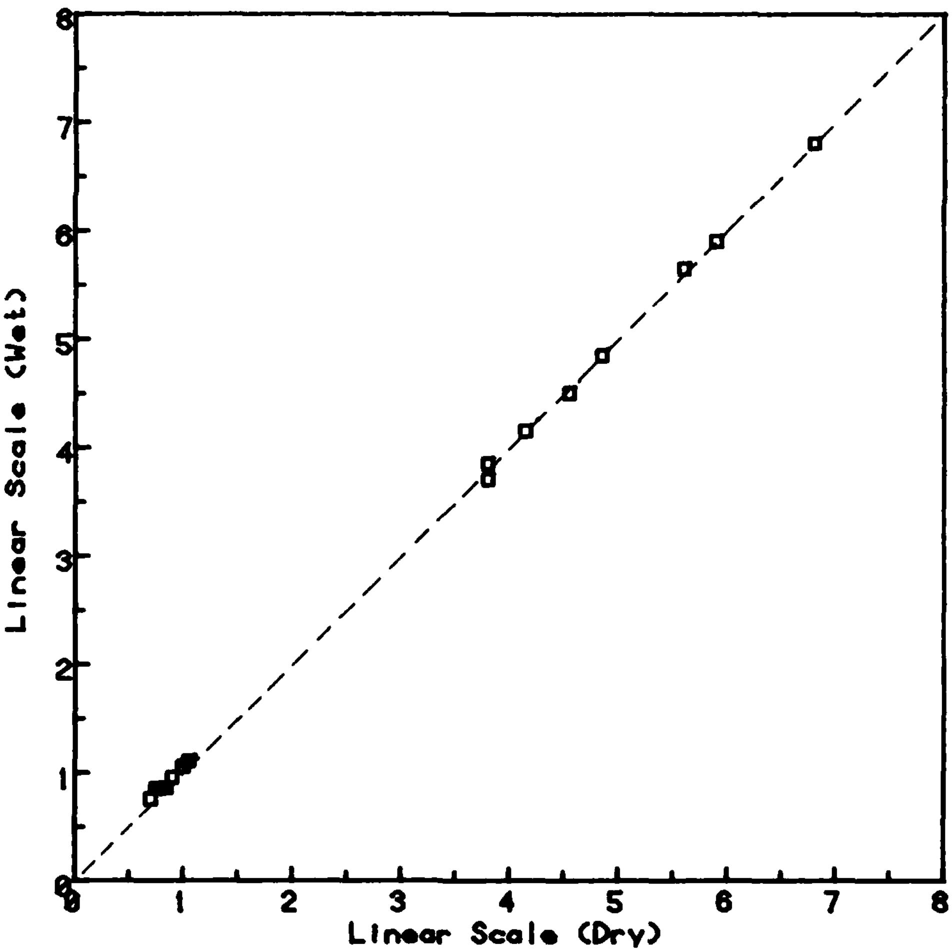
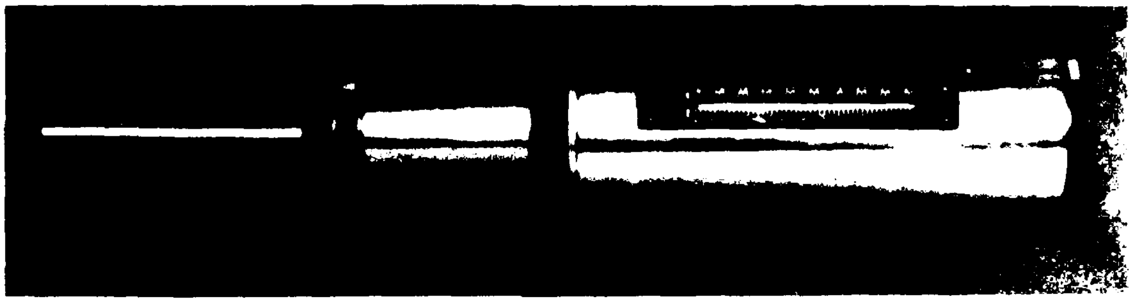
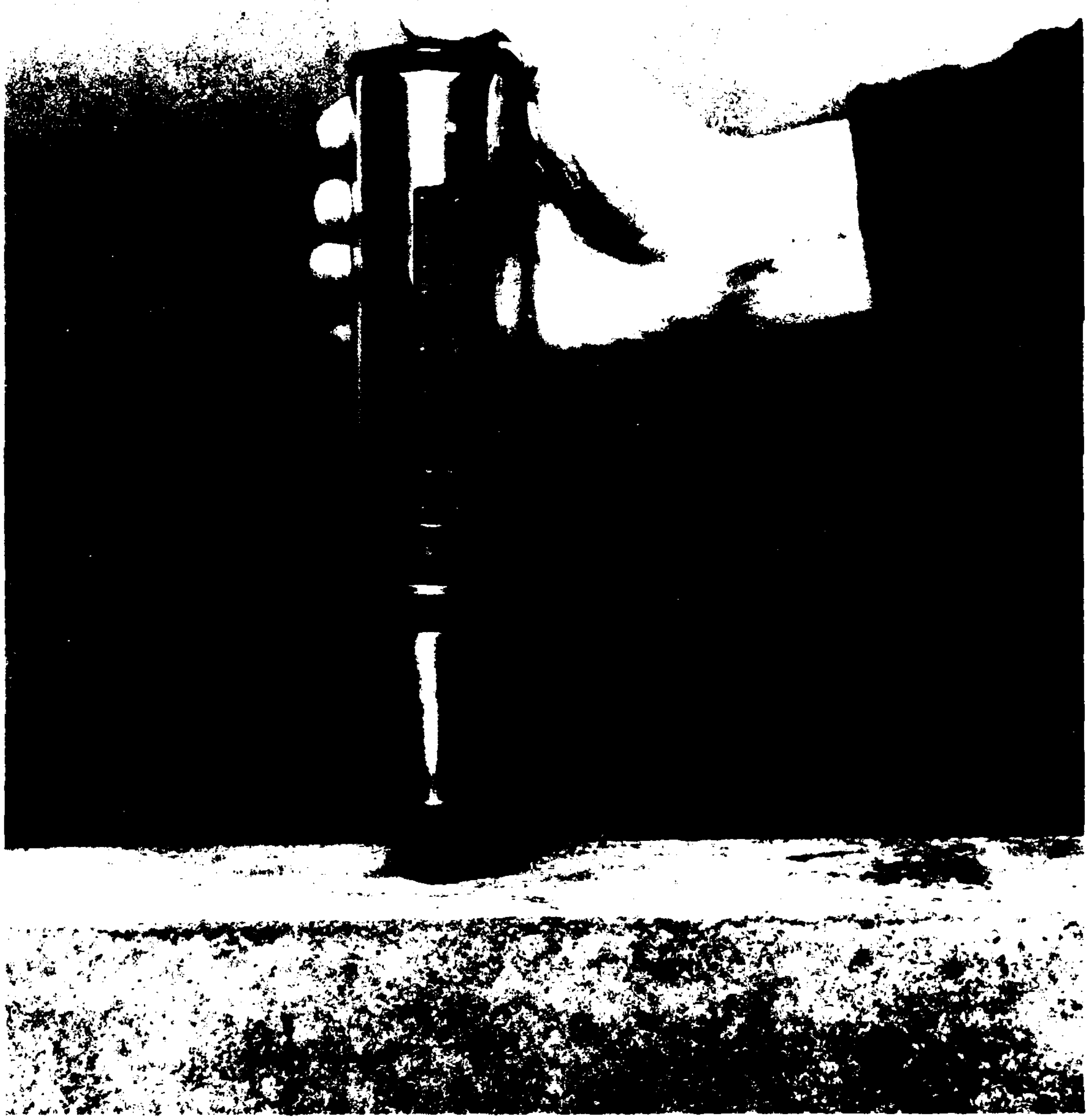


Figure 7. Plot comparing R-Meter readings before and after modification for underwater use.



(a) General view of Schmidt Hammer.



(b) Operating the Schmidt Hammer.

Figure 8. Schmidt Hammer, Model RM 710, Type L.

1. Impact plunger
2. Test specimen
3. Housing
4. Rider with guide rod
5. Scale
6. Pushbutton
7. Hammer guide bar
8. Disk
9. Cap
10. Two-part ring
11. Rear cover
12. Compression spring
13. Pawl
14. Hammer mass
15. Retaining spring
16. Impact spring
17. Guide sleeve
18. Felt washer
19. Plexiglass window
20. Trip screw
21. Lock nut
22. Pin
23. Pawl spring

A. Front fixation of impact spring

B. Rear end of impact spring engaged to hammer mass

Note:
(a) Plunger (1) in impacted position

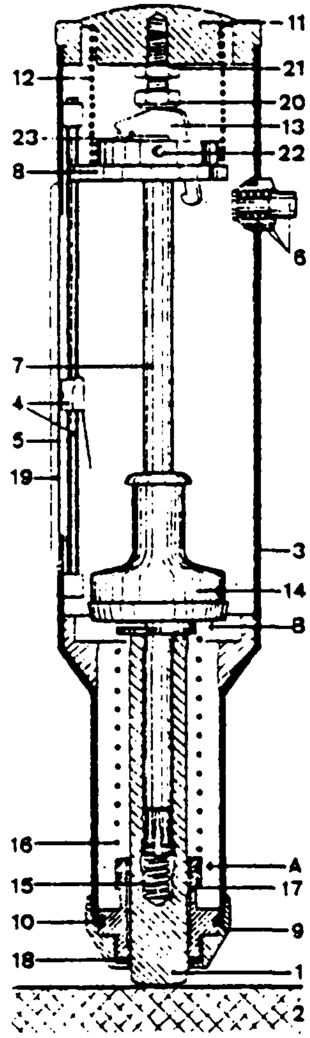


Figure 9. Cutaway view of Schmidt Hammer, Model RM 710, Type L.

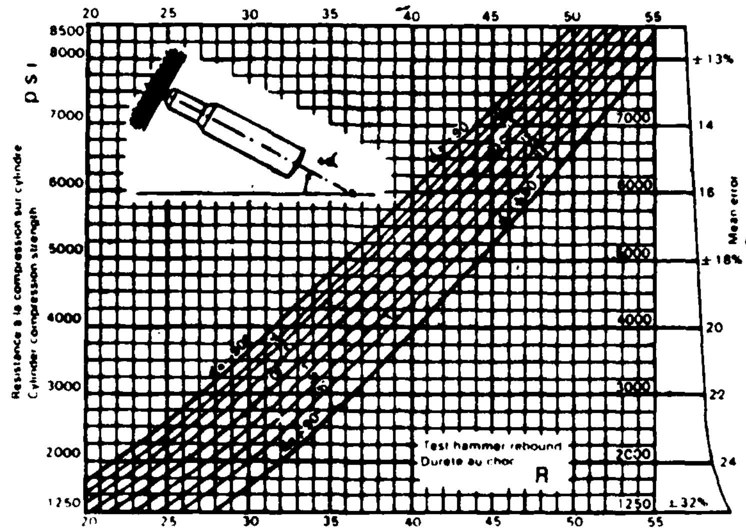


Figure 10. General calibration chart that relates rebound number to cylinder compressive strength for the Model RM 710, Schmidt Hammer.

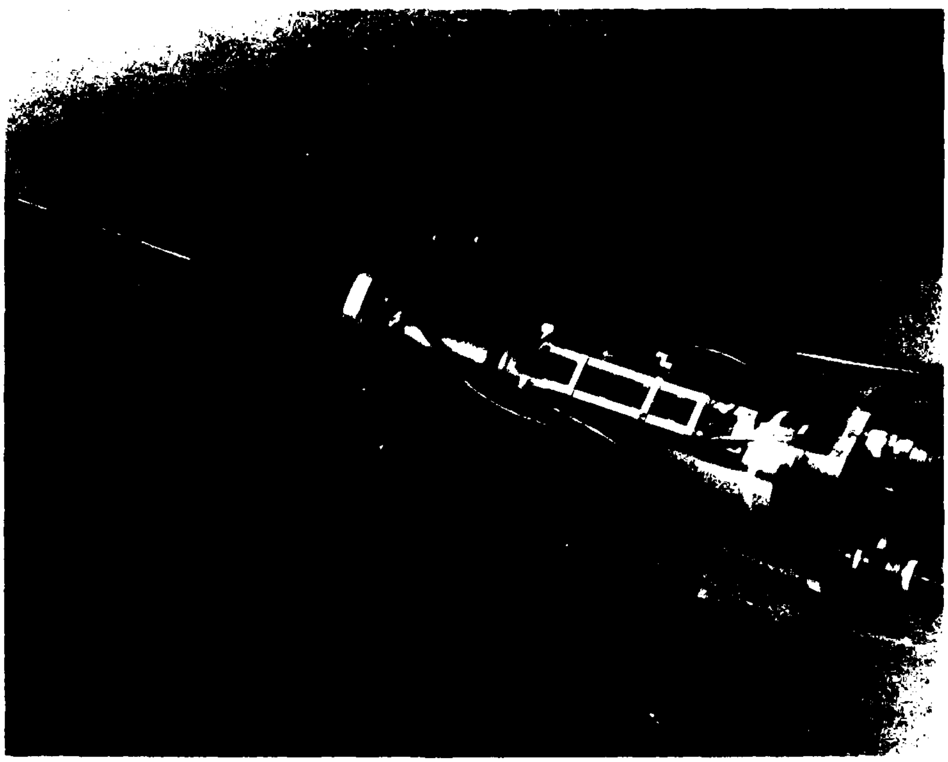


Figure 11. Schmidt Hammer modified for underwater use.

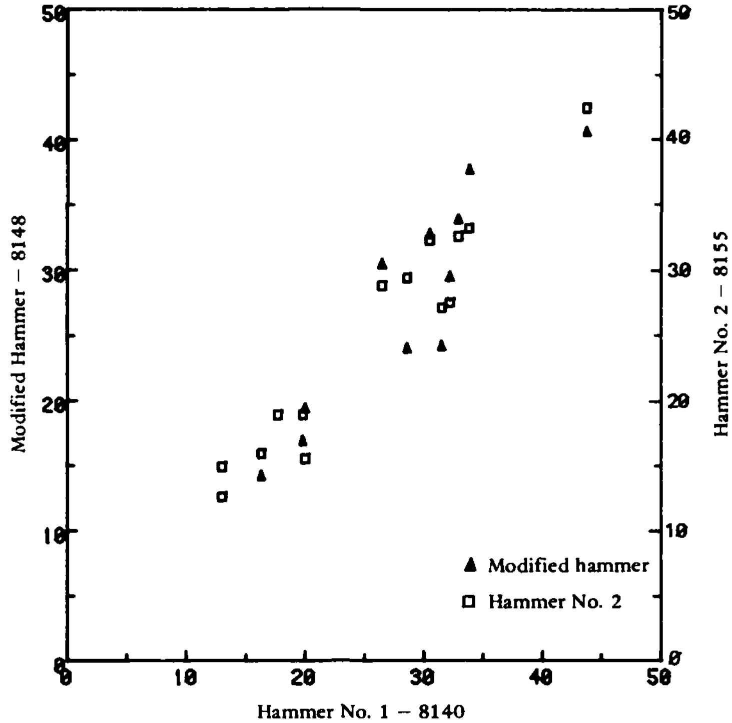


Figure 12. Plot of Schmidt Hammer data - dry.

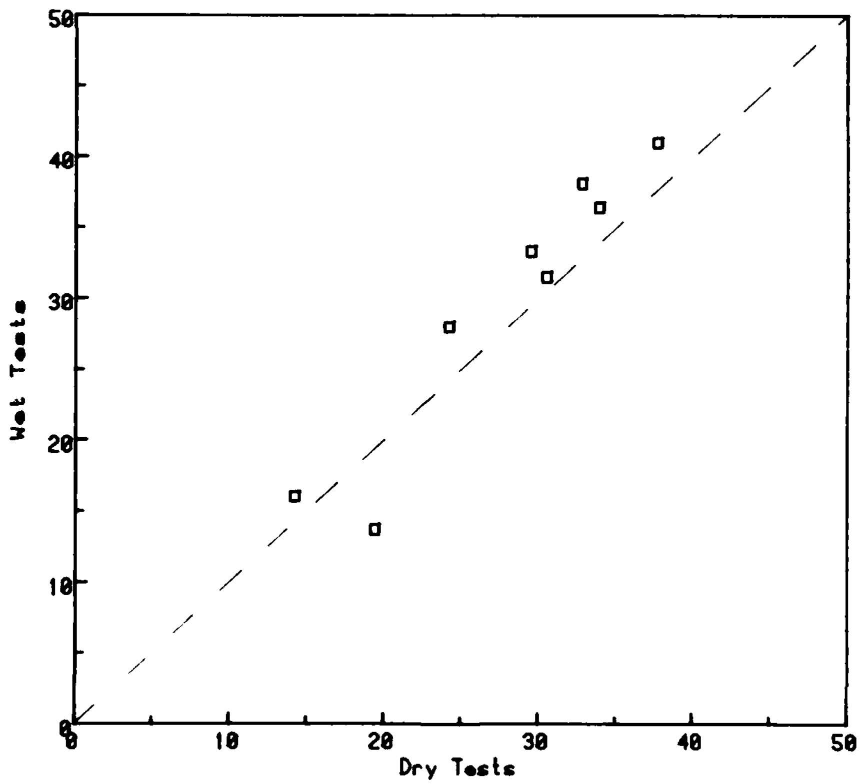


Figure 13. Plot of modified Schmidt Hammer data.

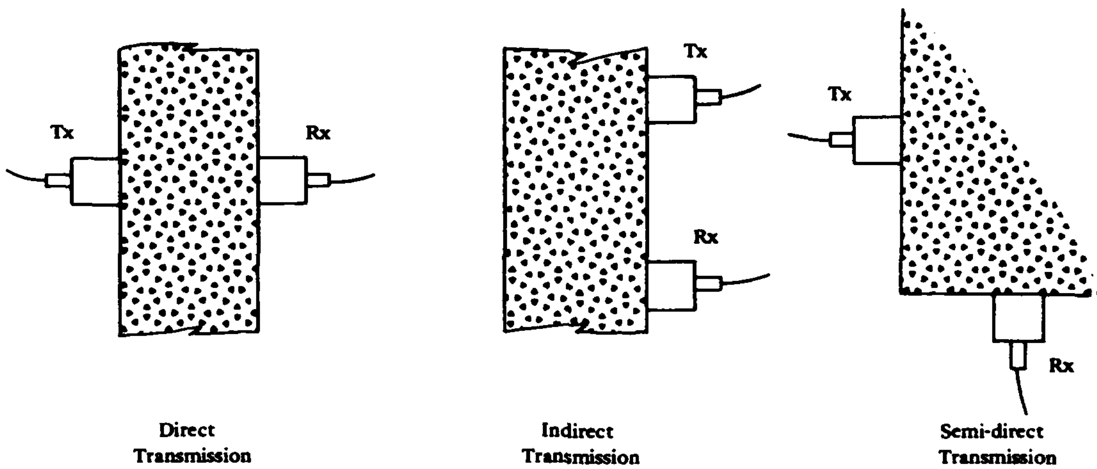
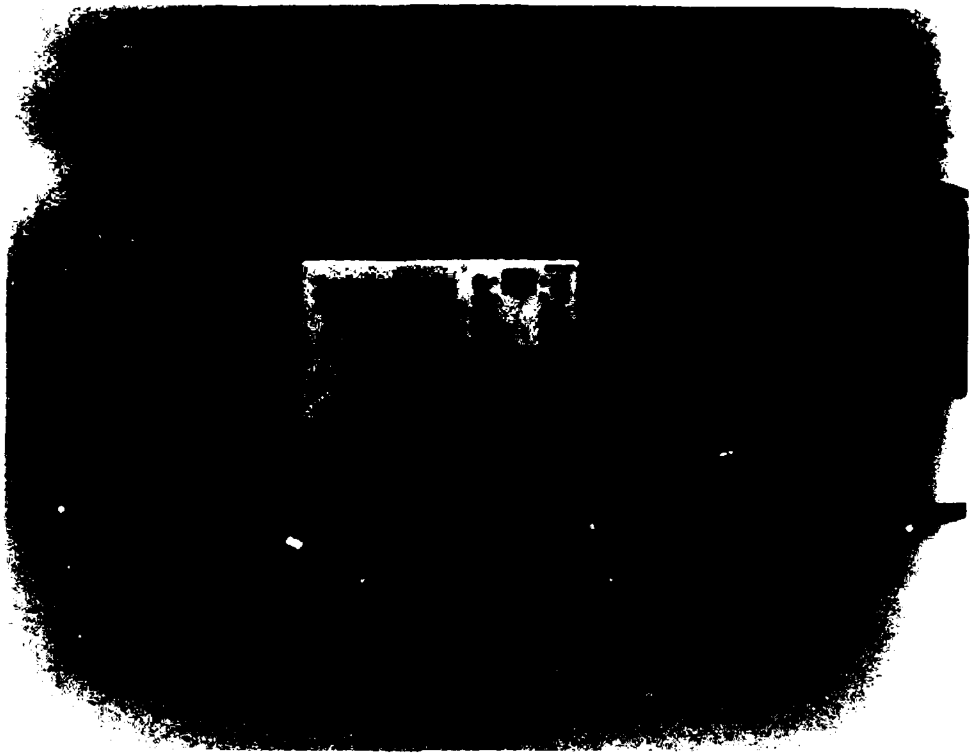
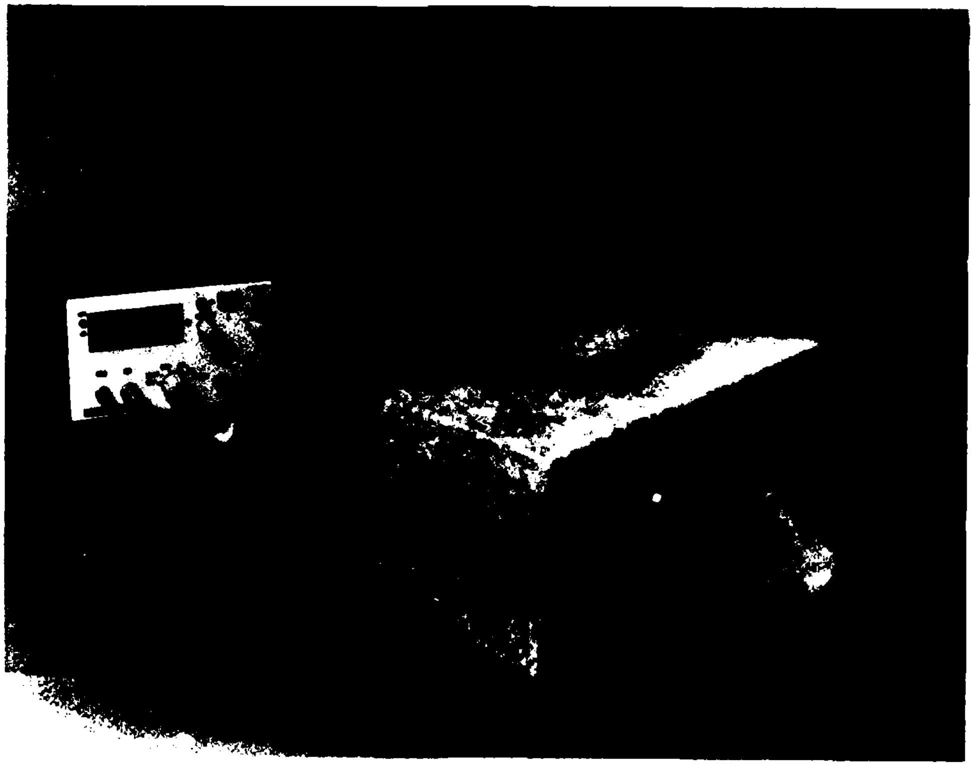


Figure 14. Methods of ultrasonic pulse transmission.



(a) General view of ultrasonic test equipment.



(b) Operating the V-Meter to collect data.

Figure 15. V-Meter, Model C-4899.

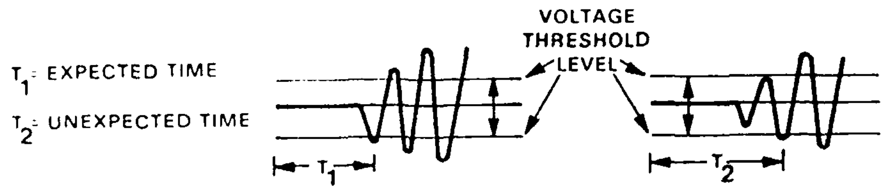


Figure 16. Detection threshold effects on transit time measurement.

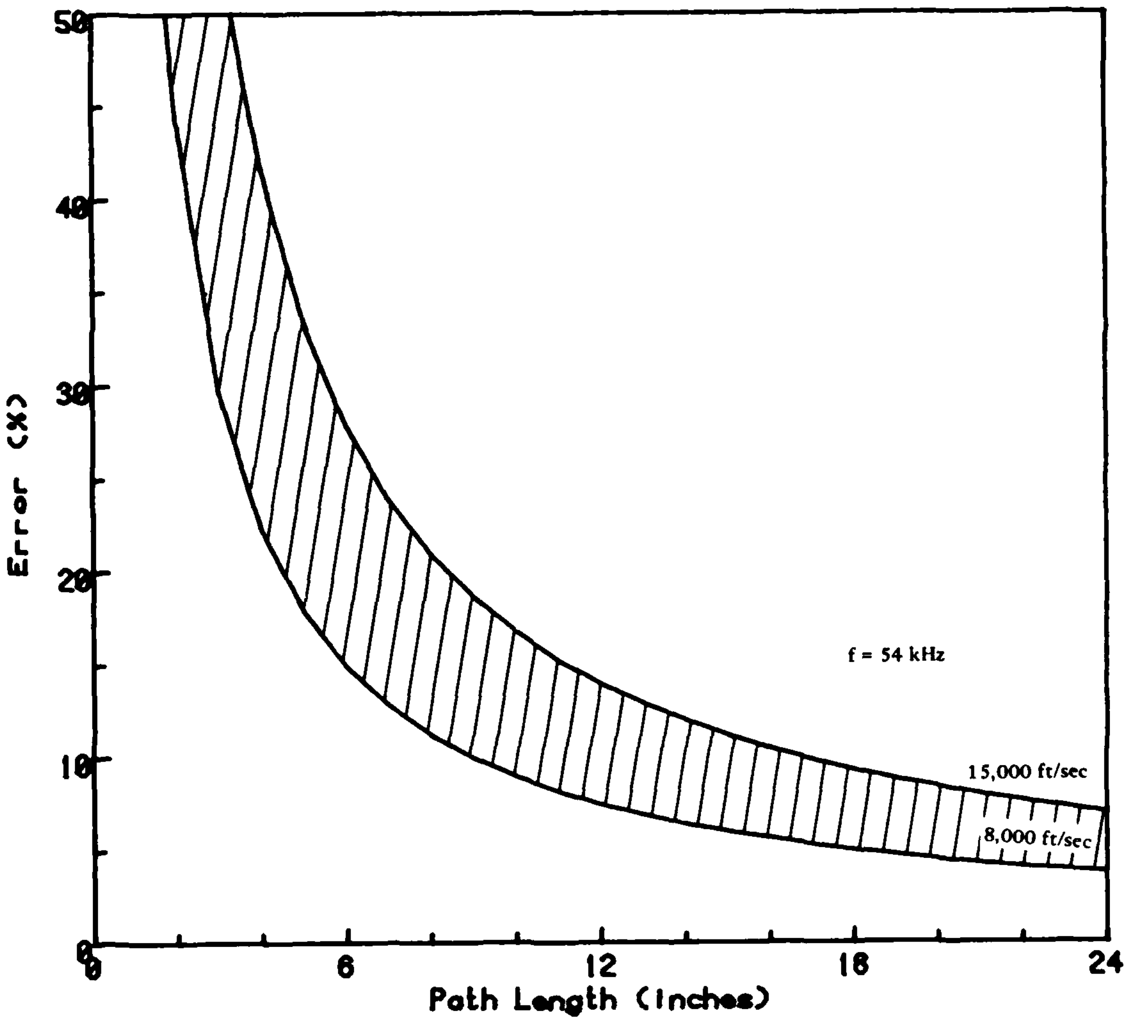


Figure 17. Half-wavelength detection error.

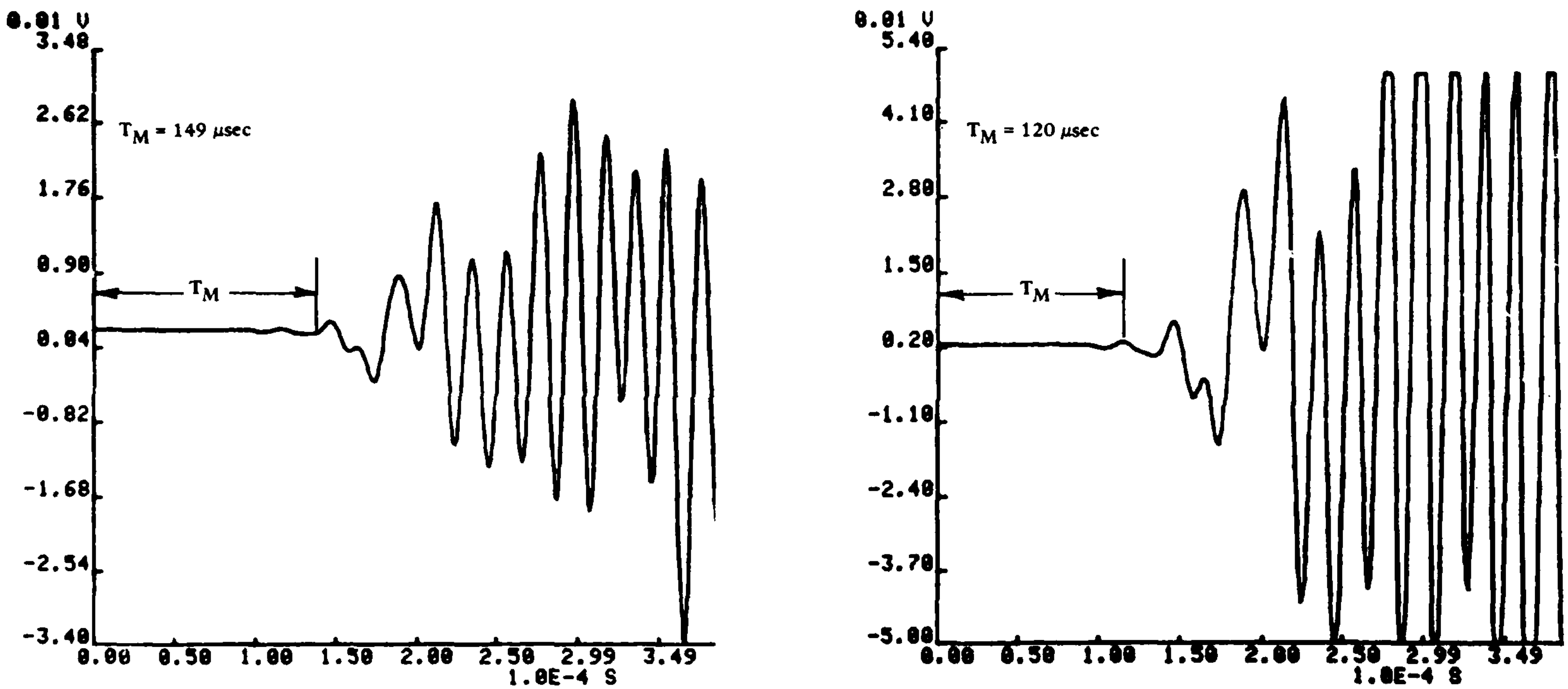


Figure 18. Signal waveforms illustrating the effect of poor acoustic coupling (left waveform) on transit time measurement.

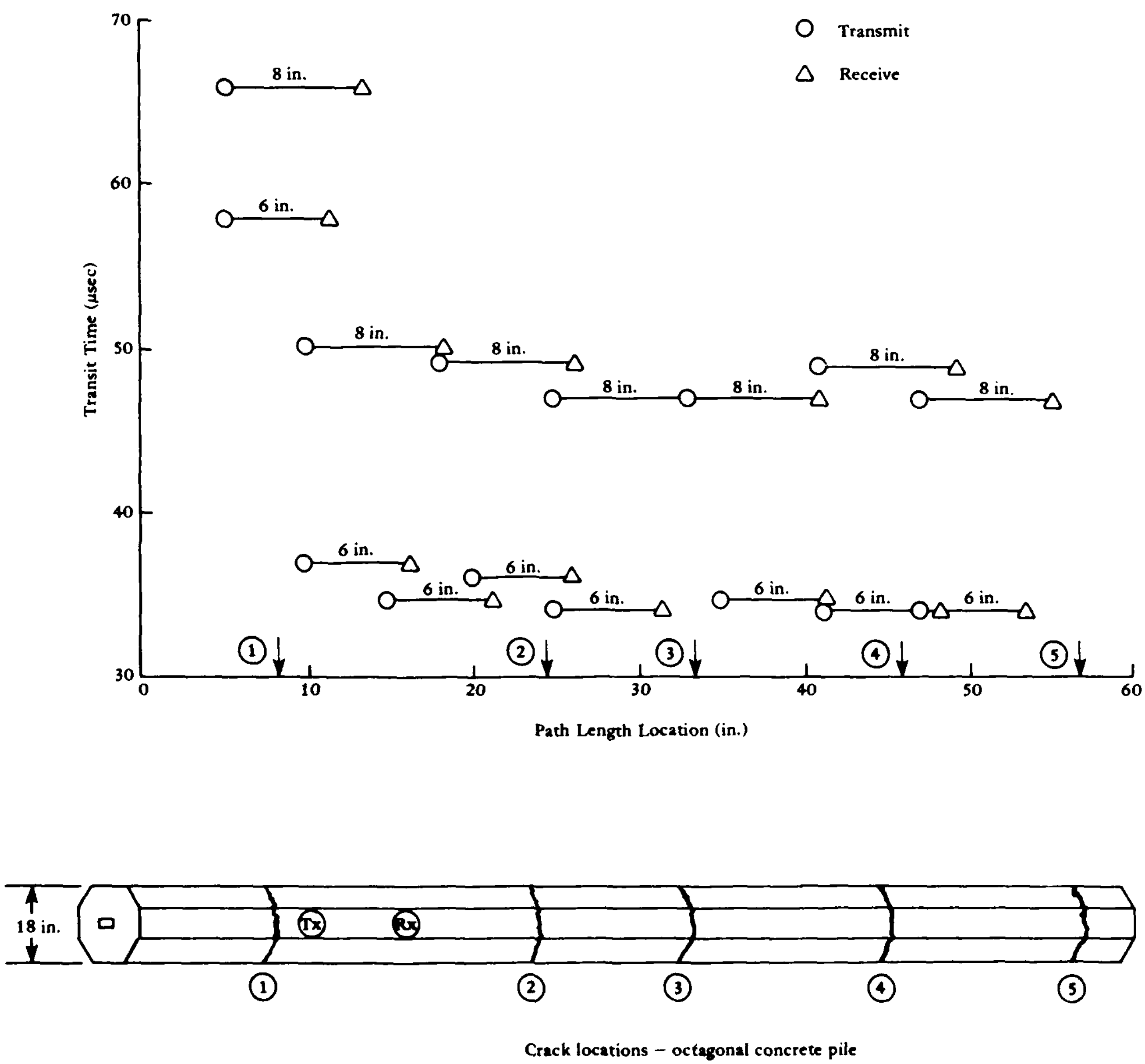


Figure 19. Measured indirect transit times as a function of position along a cracked prestressed concrete pile.

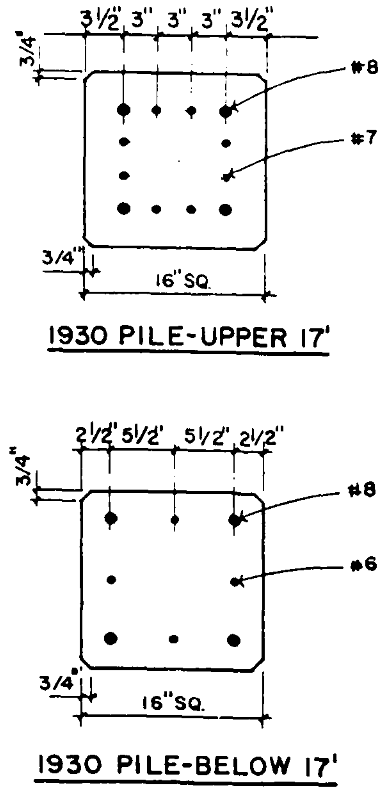


Figure 20. Cross-section view of 1930 piles, Pier J/K.

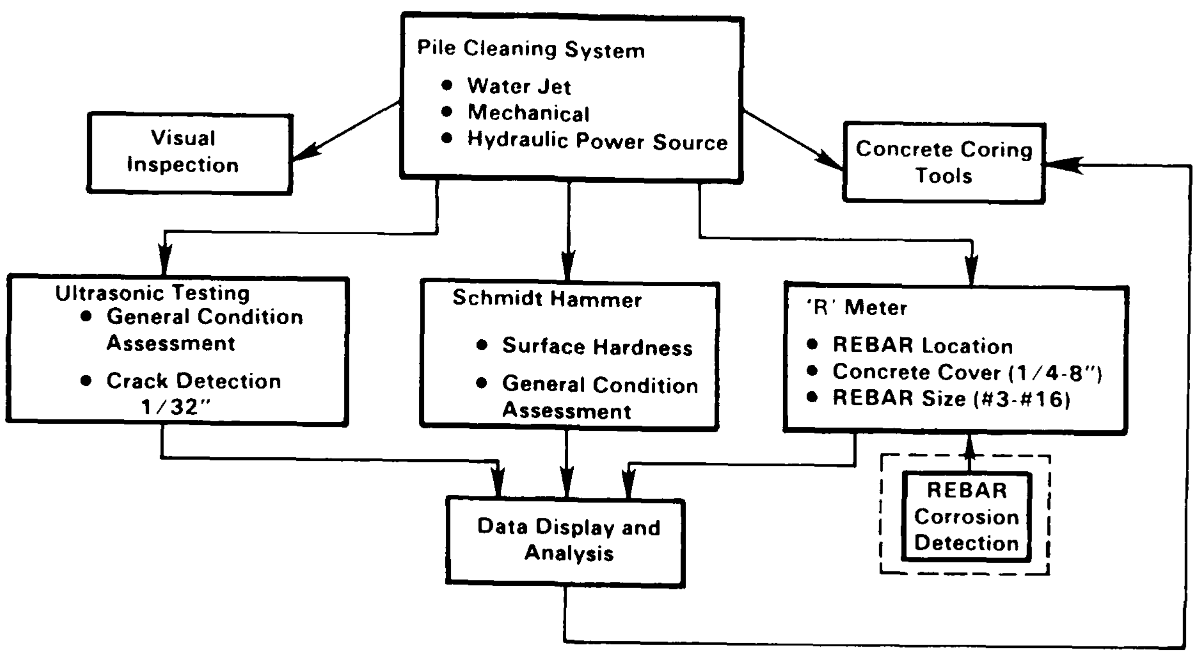


Figure 21. Integrated Systems Approach to Underwater Concrete Inspection.

Appendix

NOMINAL DIMENSIONS OF REINFORCING STEEL

Table A-1. Nominal Dimensions of Reinforcing Steel

Number	Diameter (inches)
2	1/4
3	3/8
4	1/2
5	5/8
6	3/4
7	7/8
8	1
9	1-1/8
10	1-1/4

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ARMY-BELVOIR R&D CTR STRBE-AALO, Ft Belvoir, VA; STRBE-BLORE, Ft Belvoir, VA; STRBE-CFLO, Fort Belvoir, VA; STRBE-GS, Fort Belvoir, VA; STRBE-WC, Ft. Belvoir, VA
ARMY-DEPOT SYS COMMAND DRSDS-AI, Chambersburg, PA
ADMINSUPU PWO, Bahrain
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CBC Code 10, Davisville, RI; Code 155, Port Hueneme, CA; Code 156, Port Hueneme, CA; Code 430, Gulfport, MS; Dir, CESO, Port Hueneme, CA; Library, Davisville, RI; PWO (Code 80), Port Hueneme, CA; PWO, Davisville, RI; PWO, Gulfport, MS; Tech Library, Gulfport, MS
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CNO Code NOP-964, Washington DC; Code OP 22, Washington, DC; Code OP 23, Washington, DC; Code OP-987J, Washington, DC; Code OPNAV 09B24 (H); OP-098, Washington, DC
COMCBLANT Code S3T, Norfolk, VA
COMCBPAC Diego Garcia Proj Offr, Pearl Harbor, HI
COMFAIRMED SCE, Naples, Italy
COMFLEACT PWC (Engr Dir), Sasebo, Japan; PWO, Okinawa, Japan; PWO, Sasebo, Japan; SCE, Yokosuka Japan
COMFLEACT, OKINAWA PWO, Kadena, Japan
COMNAVACT PWO, London, England
COMNAVAIRLANT Nuc Wpns Sec Offr, Norfolk, VA
COMNAVLOGPAC Code 4318, Pearl Harbor, HI
COMNAVMEDCOM Code 43, Washington, DC
COMNAVRESFOR Code 08, New Orleans, LA
COMNAVSUPPFORANTARCTICA DET, PWO, Christchurch, NZ
COMNAVSURFLANT CO, Norfolk, VA; Code N42A Norfolk, VA
COMNAVSURFPAC Code N-4, San Diego, CA
COMOCEANSYSLANT Fac Mgmt Offr, PWD, Norfolk, VA
COMOCEANSYSPAC SCE, Pearl Harbor, HI
COMSPAWARSYSCOM Code PME 124-61, Washington, DC; PME 124-612, Washington, DC
COMSUBDEVGRUONE CO, San Diego, CA; Ops Offr, San Diego, CA
COMTRALANT SCE, Norfolk, VA
NAVOCEANCOMCEN CO, Guam, Mariana Islands; Code EES, Guam, Mariana Islands
NAVRESCEN PE-PLS, Tampa, FL
DEFFUELSUPPCEN DFSC-OWE, Alexandria VA
DIA DB-6E1, Washington, DC; DB-6E2, Washington, DC
DIRSSP Tech Lib, Washington, DC
DLSIE Army Logistics Mgt Center, Fort Lee, VA

DOE Wind/Ocean Tech Div, Tobacco, MD
DTIC Alexandria, VA
DTNSRDC Code 1706 (Alnutt), Bethesda, MD; Code 172, Bethesda, MD; Code 4111 (R. Gierich), Bethesda MD; Code 42, Bethesda MD; DET, Code 2724, Annapolis, MD; DET, Code 284, Annapolis, MD; DET, Code 4120, Annapolis, MD; DET, Code 522 (Library), Annapolis, MD
ENVIRONMENTAL PROTECTION AGENCY ANR-458, Washington, DC
EODGRU ONE DET, CO, Point Mugu, CA
FAA Code APM-740 (Tomita), Washington, DC
FCTC LANT, PWO, Virginia Bch, VA
FMFLANT CEC Offr, Norfolk VA
FOREST SERVICE Engrg Staff, Washington, DC
GIDEP OIC, Corona, CA
GSA Code FAIA, Washington, DC
IRE-ITTD Input Proc Dir (R. Danford), Eagan, MN
KWAJALEIN MISRAN BMDSC-RKL-C
LIBRARY OF CONGRESS Sci & Tech Div, Washington, DC
MARCORDIST 12, Code 4, San Francisco, CA
MARCORPS FIRST FSSG, Engr Supp Offr, Camp Pendleton, CA
MARCORPS AIR/GND COMBAT CTR ACOS Fac Engr, Okinawa
MARINE CORPS BASE ACOS Fac engr, Okinawa; Code 4.01, Camp Pendleton, CA; Code 406, Camp Lejeune, NC; Dir, Maint Control, PWD, Okinawa, Japan; M & R Division, Camp Lejeune NC; Maint Ofc, Camp Pendleton, CA; PWO, Camp Lejeune, NC; PWO, Camp Pendleton CA
MARINE CORPS HQTRS Code LFF-2, Washington DC
MARITIME ADMIN B&D, Washington, DC
MCAF Code C144, Quantico, VA
MCAS Dir, Fac Engrg Div, Cherry Point, NC; Dir, Ops Div, Fac Maint Dept, Cherry Point, NC; PWO, Kaneohe Bay, HI; PWO, Yuma, AZ
MCDEC M & L Div Quantico, VA; PWO, Quantico, VA
MCRD SCE, San Diego CA
NAF Dir, Engrg Div, PWD, Atsugi, Japan; PWO, Atsugi Japan
NALF OIC, San Diego, CA
NAS Code 0L, Alameda, CA; Code 163, Keflavik, Iceland; Code 182, Bermuda; Code 18700, Brunswick, ME; Code 6234 (G. Trask), Point Mugu CA; Code 70, Marietta, GA; Code 72E, Willow Grove, PA; Code 83, Patuxent River, MD; Code 8E, Patuxent River, MD; Code 8EN, Patuxent River, MD; Dir, Engrg Div, Millington, TN; Dir, Maint Control Div, Key West, FL; Director, Engrg, Div; Engr Dept, PWD, Adak, AK; Engrg Dir, PWD, Corpus Christi, TX; Fac Plan Br Mgr (Code 183), NI, San Diego, CA; Lead CPO, PWD, Self Help Div, Beeville, TX; Oceana, PWO, Virginia Bch, VA; P&E (Code 1821H), Miramar, San Diego, CA; PWD Maint Div, New Orleans, LA; PWD, Maintenance Control Dir., Bermuda; PWO, Beeville, TX; PWO, Cecil Field, FL; PWO, Dallas TX; PWO, Glenview IL; PWO, Keflavik, Iceland; PWO, Key West, FL; PWO, Kingsville TX; PWO, Millington, TN; PWO, Miramar, San Diego, CA; PWO, Moffett Field, CA; PWO, New Orleans, LA; PWO, Sigonella, Sicily; PWO, South Weymouth, MA; PWO, Willow Grove, PA; SCE, Barbers Point, HI; SCE, Cubi Point, RP; Security Offr (Code 15), Alameda, CA; Security Offr, Kingsville, TX
NATL BUREAU OF STANDARDS B-348 BR, Gaithersburg, MD
NATL RESEARCH COUNCIL Naval Studies Board, Washington, DC
NAVADMINCOM SCE, San Diego, CA
NAVAIRDEVCEN Code 813, Warminster PA
NAVAIRENGCEN Dir, Engrg (Code 182), Lakehurst, NJ; PWO, Lakehurst, NJ
NAVAIREWORKFAC Code 100, Cherry Point, NC; Code 640, Pensacola FL; Code 64116, San Diego, CA; Equip Engr Div (Code 61000), Pensacola, FA; SCE, Norfolk, VA
NAVAIRPROPTESTCEN CO, Trenton, NJ
NAVAIRTESTCEN PWO, Patuxent River, MD
NAVAUDSVCHQ Director, Falls Church VA
NAVAVIONICCEN Deputy Dir, PWD (Code D/701), Indianapolis, IN; PW Div, Indianapolis, IN
NAVCAMS PWO, Norfolk VA; SCE (Code N-7), Naples, Italy; SCE, Guam, Mariana Islands; SCE, Wahiawa HI; SCE, Wahiawa, HI; Security Offr, Wahiawa, HI
NAVCHAPGRU Code 60, Williamsburg, VA
NAVCOASTSYSCEN Code 2230 (J. Quirk) Panama City, FL; Code 423, Panama City, FL; Code 630, Panama City, FL; Code 715 (J. Mittleman) Panama City, FL; Code 719, Panama City, FL; Tech Library, Panama City, FL
NAVCOMMSTA Code 401, Nea Makri, Greece; Dir, Maint Control, PWD, Diego Garcia; Dir, Maint Control, PWD, Thurso, UK; PWO, Exmouth, Australia
NAVCONSTRACEN Code B-1, Port Hueneme, CA
NAVEDTRAPRODEVCEN Tech Lib, Pensacola, FL
NAVELEXCEN DET, OIC, WINTER HARBOR, ME
NAVENVIRHLTHCEN Code 642, Norfolk, VA

NAVEODTECHCEN Tech Library, Indian Head, MD
NAVFAC Maint & Stores Offr, Bermuda; PWO, Centerville Bch, Ferndale CA
NAVFACENGCOM Code 03, Alexandria, VA; Code 03T (Essoglou), Alexandria, VA; Code 04A1, Alexandria, VA; Code 04B (M. Yachnis), Alexandria, VA; Code 04B3, Alexandria, VA; Code 04M, Alexandria, VA; Code 04M1A, Alexandria, VA; Code 04T1B (Bloom), Alexandria, VA; Code 04T4, Alexandria, VA; Code 04T5, Alexandria, VA; Code 051A, Alexandria, VA; Code 07A (Herrmann), Alexandria, VA; Code 07M (Gross), Alexandria, VA; Code 09M124 (Tech Lib), Alexandria, VA; Code 100, Alexandria, VA; Code 1002B, Alexandria, VA; Code 1113, Alexandria, VA; Code 113C, Alexandria, VA
NAVFACENGCOM - CHES DIV. Code 101, Washington, DC; Code 403, Washington, DC; Code 405, Washington, DC; Code 406C, Washington, DC; Code 407 (D Scheesele) Washington, DC; Code FPO-1C Washington DC; Code FPO-1E, Washington, DC; Code FPO-1E, Washington, DC; FPO-1, Washington, DC; FPO-1P/1P3, Washington, DC
NAVFACENGCOM - LANT DIV. Br Ofc, Dir, Naples, Italy; Code 1112, Norfolk, VA; Code 403, Norfolk, VA; Library, Norfolk, VA
NAVFACENGCOM - NORTH DIV. CO, Philadelpnia, PA; Code 04, Philadelphia, PA; Code 04AL, Philadelphia PA; Code 09P, Philadelphia, PA; Code 11, Philadelphia, PA; Code 111, Philadelphia, PA; Code 405, Philadelphia, PA
NAVFACENGCOM - PAC DIV. (Kyi) Code 101, Pearl Harbor, HI; Code 09P, Pearl Harbor, HI; Code 2011, Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor, HI; Library, Pearl Harbor, HI
NAVFACENGCOM - SOUTH DIV. Code 1112, Charleston, SC; Code 405, Charleston, SC; Code 406, Charleston, SC; Geotech Section (Code 4022), Charleston, SC; Library, Charleston, SC
NAVFACENGCOM - WEST DIV. 09P/20, San Bruno, CA; Code 04B, San Bruno, CA; Code 102, San Bruno, CA; Dir, PWD (Code 018), San Bruno, CA; Library (Code 04A2.2), San Bruno, CA; RDT&E LnO, San Bruno, CA
NAVFACENGCOM CONTRACTS AROICC, Quantico, VA; Code 460, Portsmouth, VA; DOICC, Diego Garcia; DROICC, Lemoore, CA; DROICC, Santa Ana, CA; OICC, Guam; OICC, Rota Spain; OICC-OICC, Virginia Beach, VA; OICC/ROICC, Norfolk, VA; ROICC (Code 495), Portsmouth, VA; ROICC, Code 61, Silverdale, WA; ROICC, Corpus Christi, TX; ROICC, Crane, IN; ROICC, Jacksonville, FL; ROICC, Keflavik, Iceland; ROICC, Key West, FL; ROICC, Point Mugu, CA; ROICC, Rota, Spain; ROICC, Twentynine Plams, CA; ROICC/AROICC, Brooklyn, NY; ROICC/AROICC, Colts Neck, NJ; ROICC/OICC, SPA, Norfolk, VA; SW Pac, Dir, Engr Div, Mania, RP; SW Pac, OICC, Manila, RP
NAVFUEL DET OIC, Yokohama, Japan
NAVHOSP CE, Newport, RI; CO, Millington, TN; Dir, Engrg Div, Camp Lejeune, NC; PWO, Guam, Mariana Islands; PWO, Okinawa, Japan; SCE (Knapowski), Great Lakes, IL; SCE, Camp Pendleton CA; SCE, Pensacola FL; SCE, Yokosuka, Japan
NAVMAG Engr Dir, PWD, Guam, Mariana Islands; SCE, Guam, Mariana Islands; SCE, Subic Bay, RP
NAVMEDCOM MIDLANT REG, PWO, Norfolk, VA; NWREG, Head, Fac Mgmt Dept, Oakland, CA; SEREG, Head, Fac Mgmt Dept, Jacksonville, FL; SWREG, Head, Fac Mgmt Dept, San Diego, CA; SWREG, OICC, San Diego, CA
NAVMEDRSHINSTITUTE Code 47, Bethesda, MD
NAVOCEANO Code 3432 (J. DePalma), Bay St. Louis MS; Code 6200 (M Paige), Bay St. Louis, MS; Library Bay St. Louis, MS
NAVOCEANSYSCEN Code 5204 (J. Stachiw), San Diego, CA; Code 6700, San Diego, CA; Code 90 (Talkington), San Diego, CA; Code 944 (H.C. Wheeler), San Diego, CA; Code 964 (Tech Library), San Diego, CA; Code 9642B (Bayside Library), San Diego, CA; DET, R Yumori, Kailua, HI; DET, Tech Lib, Kailua, HI
NAVORDMISTESTSTA Dir, Engrg, PWD, White Sands, NM
NAVORDSTA PWO, Louisville, KY
NAVPETOFF Code 30, Alexandria, VA
NAVPGSCOL C. Morers, Monterey, CA; Code 68 (C.S. Wu), Monterey, CA; E. Thornton, Monterey, CA; Haderlie, Monterey, CA
NAVPHIBASE Harbor Clearance Unit Two, Norfolk, VA; PWO, Norfolk, VA; SCE, San Diego, CA
NAVRADRECFAC PWO, Kami Seya Japan
NAVRESREDCOM Commander (Code 072), San Francisco, CA
NAVSCOLCECOFF C35 Port Hueneme, CA; Code C44A, Port Hueneme, CA
NAVSCSCOL PWO, Athens GA
NAVSEACENPAC Code 32, Sec Mgr, San Diego, CA
NAVSEASYSCOM Code 035, Washington DC; Code 05E1, Washington, DC; Code 06H4, Washington, DC; Code 644, Washington, DC; Code CEL-TD23, Washington, DC; Code OOC-D, Washington, DC; Code PMS 395 A2, Washington, DC; Code PMS-396.3211 (J. Rekas) Washington, DC; Code SEA-99611, Washington, DC; PMS-395 A1, Washington, DC; SEA 05E1, Washington, DC; SEA-05R4 (J. Freund), Washington, DC
NAVSECGRUACT CO, Galeta Island, Panama Canal; PWO (Code 40), Edzell, Scotland; PWO, Adak AK; PWO, Sabana Seca, PR
NAVSECGRUCOM Code G43, Washington, DC

NAVSECSTA Dir, Engrg, PWD, Washington, DC
NAVSHIPREPFAC Library, Guam; SCE, Subic Bay, RP; SCE, Yokosuka Japan
NAVSHIPYD CO, Philadelphia, PA; Carr Inlet Acoustic Range, Bremerton, WA; Code 134, Pearl Harbor, HI; Code 202.4, Long Beach, CA; Code 202.5 (Library), Bremerton, WA; Code 280, Mare Is., Vallejo, CA; Code 280.28 (Goodwin), Vallejo, CA; Code 380, Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 410, Mare Is., Vallejo CA; Code 440, Bremerton, WA; Code 440, Bremerton, WA; Code 440, Portsmouth, NH; Code 440, Portsmouth, VA; Code 440.4, Bremerton, WA; Code 457 (Maint Supr), Vallejo, CA; Code 903, Long Beach, CA; Dir, Maint Control, PWD, Long Beach, CA; Dir, PWD (Code 420), Portsmouth, VA; Library, Portsmouth, NH; PWD (Code 450-HD), Portsmouth, VA; PWD (Code 457-HD) Shop 07, Portsmouth, VA; PWO, Bremerton, WA; PWO, Charleston, SC; PWO, Mare Island, Vallejo, CA; SCE, Pearl Harbor, HI
NAVSTA A. Sugihara, Pearl Harbor, HI; CO, Brooklyn, NY; CO, Long Beach, CA; CO, Roosevelt Roads, PR; Code 18, Midway Island; Dir, Engr Div, PWD (Code 18200), Mayport, FL; Dir, Engr Div, PWD, Guantanamo Bay, Cuba; Dir, Mech Engr, Norfolk, VA; Engrg Dir, Rota, Spain; Maint Control Div, Guantanamo Bay, Cuba; PWO, Guantanamo Bay, Cuba; PWO, Mayport, FL; SCE, Guam, Marianas Islands; SCE, Pearl Harbor HI; SCE, San Diego CA; SCE, Subic Bay, RP; Util Engrg Offr, Rota, Spain
NAVSUPPACT PWO, Holy Loch, UK; PWO, Naples, Italy
NAVSUPPFAC Dir, Maint Control Div, PWD, Thurmont, MD
NAVSUPPO Security Offr, La Maddalena, Italy
NAVSURFWPNCEN Code E211 (C. Rouse), Dahlgren, VA; DET, PWO, White Oak, Silver Spring, MD; PWO, Dahlgren, VA
NAVTECHTRACEN SCE, Pensacola FL
NAVWARCOL Fac Coord (Code 24), Newport, RI; Lib Serials, Newport, RI
NAVWPNCEN Code 2634, China Lake, CA; Code 2636, China Lake, CA; DROICC (Code 702), China Lake, CA; PWO (Code 266), China Lake, CA
NAVWPNSFAC Wpns Offr, St. Mawgan, England
NAVWPNSTA Code 092, Colts Neck, NJ; Code 092, Concord CA; Dir, Maint Control, PWD, Concord, CA; Dir, Maint Control, Yorktown, VA; Engrg Div, PWD, Yorktown, VA; K.T. Clebak, Colts Neck, NJ; PWO, Charleston, SC; PWO, Code 09B, Colts Neck, NJ; PWO, Seal Beach, CA
NAVWPNSTA PWO, Yorktown, VA
NAVWPNSTA Supr Gen Engr, PWD, Seal Beach, CA
NAVWPNSUPPCEN Code 09, Crane, IN
NETC Code 42, Newport, RI; PWO, Newport, RI
COMEODGRU OIC, Norfolk VA
NCR 20, CO, Gulfport, MS; 20, Code R70
NMCB 3, SWC D. Wellington; 74, CO; FIVE, Operations Dept; Forty, CO; THREE, Operations Off.
NOAA Joseph Vadus, Rockville, MD; Library, Rockville, MD; M Ringenbach, Rockville, MD
NORDA Code 410, Bay St. Louis, MS; Ocean Prog Off (Code 500), Bay St. Louis, MS; Ocean Rsch Off (Code 440), Bay St. Louis, MS
NRL Code 5800 Washington, DC; Code 6120 (R. Brady Jr), Washington, DC
USCG Code 2511 (Civil Engrg), Washington, DC
NSC Cheatham Annex, PWO, Williamsburg, VA; Code 54.1, Norfolk, VA; Code 700, Norfolk, VA; Fac & Equip Div (Code 43) Oakland, CA; SCE, Charleston, SC; SCE, Norfolk, VA
NSD SCE, Subic Bay, RP
CBU 401, OICC, Great Lakes, IL
NUSC DET Code 3322 (Brown), New London, CT; Code 3322 (Varley) New London, CT; Code EA123 (R.S. Munn), New London, CT; Code TA131 (G. De la Cruz), New London CT
OCNR Code 126, Arlington, VA
OFFICE SECRETARY OF DEFENSE OASD (MRA&L) Dir of Energy, Washington, DC
CNR DET, Code481, Bay St. Louis, MS; DET, Dir, Boston, MA
OCNR Code 421 (Code E.A. Silva), Arlington, VA; Code 700F, Arlington, VA
PACMISRANFAC PWO, Kauai, HI
PERRY OCEAN ENG R. Pellen, Riviera Beach, FL
PHIBCB 1, CO, San Diego, CA; 1, ELCAS Offcr, San Diego, Ca; 1, P&E, San Diego, CA; 2, Co, Norfolk, VA
PMTC Code 3144, (E. Good) Point Mugu, CA; Code 5041, Point Mugu, CA; Code 5054-S, Point Mugu, CA
PWC ACE Office, Norfolk, VA; Code 10, Great Lakes, IL; Code 10, Oakland, CA; Code 100, Guam, Mariana Islands; Code 101 (Library), Oakland, CA; Code 110, Oakland, CA; Code 123-C, San Diego, CA; Code 200, Guam, Mariana Islands; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 422, San Diego, CA; Code 423, San Diego, CA; Code 424, Norfolk, VA; Code 425 (L.N. Kaya, P.E.), Pearl Harbor, HI; Code 438 (Aresto), San Diego, CA; Code 500, Norfolk, VA; Code 500, Oakland, CA; Code 505A, Oakland, CA; Code 590, San Diego, CA; Code 610, San Diego Ca; Code 700, San Diego, CA; Dir Maint Dept (Code 500), Great Lakes, IL; Dir, Maint Control, Oakland, CA; Dir, Serv Dept (Code 400), Great Lakes, IL; Dir, Transp Dept (Code 700), Great Lakes, IL; Dir, Util Dept (Code 600), Great Lakes, IL; Fac Plan Dept (Code 1011), Pearl Harbor, HI; Library (Code 134), Pearl Harbor, HI; Library, Guam, Mariana Islands; Library, Norfolk, VA; Library,

Pensacola, FL; Library, Yokosuka JA; Prod Offr, Norfolk, VA; Tech Library, Subic Bay, RP; Util Offr, Guam, Mariana Island
SEAL TEAM 6, Norfolk, VA
SPCC PWO (Code 08X), Mechanicsburg, PA
SUBASE SCE, Pearl Harbor, HI
SUBRESUNIT Sea Cliff DSV4, OIC, San Diego, CA; Turtle DSV-3, OIC, San Diego, CA
SUPSHIP Tech Library, Newport News, VA
HAYNES & ASSOC H. Haynes, P.E., Oakland, CA
UCT ONE CO, Norfolk, VA
UCT TWO CO, Port Hueneme, CA
U.S. MERCHANT MARINE ACADEMY Reprint Custodian, Kings Point, NY
US DEPT OF INTERIOR Bur of Land Mgmnt (Code 583), Washington, DC; Nat'l Park Svc, RMR/PC, Denver, CO
US GEOLOGICAL SURVEY F Dyhrkopp, Metairie, LA; Marine Geology Offc (Piteleki), Reston, VA; Marine Oil & Gas Ops (R Krahl), Reston, VA
US NATIONAL MARINE FISHERIES SERVICE Sandy Hook Lab, Lib, Highlands, NY
USAF SCHOOL OF AEROSPACE MEDICINE Hyperbaric Med Div, Brooks AFB, TX
USCG Code G-EOE-4, Washington, DC; Hqtrs Library, Washington, DC
USCG R&D CENTER CO, Groton, CT; Library, Groton, CT; Ocean Sys Br, Groton, CT
USCINC PAC, Code J44, Camp HM Smith, HI
USDA Ext Serv (T Maher), Washington, DC; For Serv, Equip Dev Cen, San Dimas, CA; Forest Prod Lab (DeGroot), Madison, WI; Forest Prod Lab, Libr, Madison, WI; Forest Serv, Reg 8, Atlanta, GA
USNA Chairman, Mech Engrg Dept, Annapolis, MD; Mech Engrg Dept (Hasson), Annapolis, MD; Mgr, Engrg, Civil Specs Br, Annapolis, MD; PWO, Annapolis, MD
USS AJAX Repair Officer, San Francisco, CA
USS FULTON WPNS Rep. Offr (W-3) New York, NY
WATER & POWER RESOURCES SERVICE Smoak, Denver, CO
ADVANCED TECHNOLOGY Ops Cen Mgr (Moss), Camarillo, CA
BERKELEY PW Engr Div (Harrison), Berkeley, CA
BROOKHAVEN NATL LAB M. Steinberg, Upton, NY
CALIF. DEPT OF FISH & GAME Marine Tech Info Cen, Long Beach, CA
CALIF. DEPT OF NAVIGATION & OCEAN DEV. G Armstrong, Sacramento, CA
CALIF. MARITIME ACADEMY Library, Vallejo, CA
CALIFORNIA STATE UNIVERSITY C.V. Chelapati, Long Beach, CA; Dr. Y.C. Kim, Los Angeles, CA; Yen, Long Beach, CA
CITY OF AUSTIN Resource Mgmt Dept (G. Arnold),Austin, TX
CITY OF LIVERMORE Project Engr (Dawkins), Livermore, CA
CLARKSON COLL OF TECH G. Batson, Potsdam, NY
COLORADO SCHOOL OF MINES Dept of Engrg (Chung), Golden, CO
CORNELL UNIVERSITY Civil & Environ Engrg (F. Kulhway), Ithaca, NY; Library, Ser Dept, Ithaca, NY
DAMES & MOORE LIBRARY Los Angeles, CA
DUKE UNIV MEDICAL CENTER CE Dept (Muga), Durham, NC
UNIVERSITY OF DELAWARE Dexter, Lewes, DE
FLORIDA ATLANTIC UNIVERSITY Boca Raton, FL (McAllister); W Hartt, Boca Raton, FL
FLORIDA INSTITUTE OF TECHNOLOGY J Schwalbe, Melbourne, FL
GEORGIA INSTITUTE OF TECHNOLOGY CE Scol (Kahn), Atlanta, GA; Mazanti, Atlanta, GA
INSTITUTE OF MARINE SCIENCES Dir, Morehead City, NC; Dir, Port Aransas, TX; Library, Port Aransas, TX
IOWA STATE UNIVERSITY CE Dept, (Handy), Ames, IA
WOODS HOLE OCEANOGRAPHIC INST. Proj Engr, Woods Hole, MA
JOHNS HOPKINS UNIV Ches Bay Rsch Inst, Rsch Lib, Shady Side, MD
LEHIGH UNIVERSITY Fritz Engrg Lab, (Beedle), Bethlehem, PA; Linderman Libr, Ser Cataloguer, Bethlehem, PA; Marine Geotech Lab (A. Richards), Bethlehem, PA
LOS ANGELES COUNTY Rd Dept (J Vicelja), Los Angeles, CA
MAINE MARITIME ACADEMY Lib, Castine, ME
MICHIGAN TECHNOLOGICAL UNIVERSITY CE Dept (Haas), Houghton, MI
MIT Engrg Lib, Cambridge, MA; Lib, Tech Reports, Cambridge, MA; RV Whitman, Cambridge, MA
NATURAL ENERGY LAB Library, Honolulu, HI
NEW MEXICO SOLAR ENERGY INST. Dr. Zwibel Las Cruces NM
NY CITY COMMUNITY COLLEGE Library, Brooklyn, NY
OKLAHOMA STATE UNIV JP Lloyd, Stillwater, OK
OREGON STATE UNIVERSITY CE Dept (Bell), Corvallis, OR; CE Dept (Grace), Corvallis, OR; CE Dept (Hicks), Corvallis, OR; Oceanography Scol, Corvallis, OR
PENNSYLVANIA STATE UNIVERSITY Applied Rsch Lab, State College, PA; Snyder, State College, PA
PORT SAN DIEGO Proj Engr, Port Fac, San Diego, CA
PORTLAND STATE UNIVERSITY H Migliore, Portland, OR

PURDUE UNIVERSITY AG Altschaeffl, Lafayette, IN; Engrg Lib, Lafayette, IN; GA Leonards, Lafayette, IN
MUSEUM OF NATL HISTORY San Diego, CA (Dr. E. Schulenberger)
SAN DIEGO STATE UNIV. Dr. Krishnamoorthy, San Diego CA; I. Noorany, San Diego, CA
SCRIPPS INSTITUTE OF OCEANOGRAPHY Deep Sea Drill Proj (Adams), La Jolla, CA
SEATTLE UNIVERSITY Schwaegler, Seattle, WA
SOUTHWEST RSCH INST J. Hokanson, San Antonio, TX; King, San Antonio, TX; R. DeHart, San Antonio TX; San Antonio, TX
STANFORD UNIVERSITY CE Dept (Gere), Stanford, CA
STATE UNIV OF NEW YORK CE Dept, Buffalo, NY
STATE UNIVERSITY OF NEW YORK Mat Sci Dept (Herman), Stony Brook, NY
TEXAS A&M UNIVERSITY Hyd Rsch Lab College Station, TX; J.M. Niedzwecki, College Station, TX; Ocean Engr Proj, College Station, TX; W.B. Ledbetter, College Station, TX
UNIVERSITY OF ALASKA Doc Collections Fairbanks, AK; Marine Science Inst. College, AK
UNIVERSITY OF CALIFORNIA A-031 (Storms) La Jolla, CA; CE Dept (Gerwick), Berkeley, CA; CE Dept (Mehta), Berkeley, CA; CE Dept (Mitchell), Berkeley, CA; CE Dept (Pintz), Berkeley, CA; CE Dept (Taylor), Davis, CA; Engrg Lib., Berkeley, CA; Marine Rsrs Inst (Spiess), La Jolla, CA; Naval Arch Dept, Berkeley, CA; Prof E.A. Pearson, Berkeley, CA; Trans Engrg Dept (Duncan), Berkeley, CA
UNIVERSITY OF FLORIDA Florida Sea Grant (C. Jones), Gainesville, FL
UNIVERSITY OF HAWAII Library (Sci & Tech Div), Honolulu, HI; Ocean Engrg Dept, Honolulu, HI
UNIVERSITY OF ILLINOIS Arch Scol (Kim), Champaign, IL; CE Dept (W. Gamble), Urbana, IL; Civil Engrg Dept (Hall), Urbana, IL; Library, Urbana, IL; M.T. Davisson, Urbana, IL; Metz Ref Rm, Urbana, IL
UNIVERSITY OF MASSACHUSETTS ME Dept (Heroneumus), Amherst, MA
UNIVERSITY OF MICHIGAN Dr. Richart, Ann Arbor, MI; G Berg, Ann Arbor, MI
UNIVERSITY OF NEBRASKA-LINCOLN Ross Ice Shelf Proj, Lincoln, NE
UNIVERSITY OF NEW HAMPSHIRE P. LaVoie, Durham, NH
UNIVERSITY OF NEW MEXICO NMERI (Falk), Albuquerque, NM
UNIVERSITY OF NOTRE DAME Katona, Notre Dame, IN
UNIVERSITY OF PENNSYLVANIA Dept of Arch (P. McCleary), Philadelphia, PA; Schl of Engrg & Applied Sci (Roll), Philadelphia, PA
UNIVERSITY OF RHODE ISLAND Pell Marine Sci Lib, Narragansett, RI
UNIVERSITY OF SO. CALIFORNIA Hancock Library, Los Angeles, CA
UNIVERSITY OF TEXAS AT AUSTIN Breen, Austin, TX; Thompson, Austin, TX
UNIVERSITY OF TEXAS MEDICAL BRANCH Structural Engrg (Dr. R.L. Yuan), Arlington, TX
UNIVERSITY OF WASHINGTON App Physics Lab, Seattle, WA; CE Dept (N. Hawkins), Seattle, WA; CE Dept, Seattle, WA; Dept of Civil Engr (Dr. Mattock), Seattle WA; Library, Seattle, WA; Scol of Oceanography (Halpern), Seattle, WA
UNIVERSITY OF WISCONSIN Great Lakes Studies, Ctr, Milwaukee, WI
VENTURA COUNTY Deputy PW Dir, Ventura, CA; PWA (Brownie) Ventura, CA
WESTERN ARCHEOLOGICAL CENTER Library, Tucson AZ
WOODS HOLE OCEANOGRAPHIC INST. Doc Lib, Woods Hole, MA
AGBABIAN ASSOC. C. Bagge, El Segundo CA
ALFRED A. YEE & ASSOC. Librarian, Honolulu, HI
AMERICAN CONCRETE INSTITUTE Library, Detroit, MI
AMETEK Offshore Rsch & Engrg Div, Santa Barbara, CA
APPLIED SYSTEMS R. Smith, Agana, Guam
ARCAIR CO. D. Young, Lancaster, OH
ARVID GRANT Olympia, WA
ATLANTIC RICHFIELD CO. R.E. Smith, Dallas, TX; Sr Staff CE, Dallas, TX
BATTELLE-COLUMBUS LABS D Frink, Columbus, OH; D Hackman, Columbus, OH
BECHTEL CORP. R. Leonard, San Francisco CA
BETHLEHEM STEEL CO. Engrg Dept (Dismuke), Bethlehem, PA
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